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CALCULATING METHOD FOR MULTI-STAGE
AXIAL COMPRESSORS WITH IMPULSE
BLADINGS AND CONSTANT TIP DIAMETER

M. H. Vavra

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SUMMARY

This report gives an approximate calculating method for the design point performance of multi-stage axial compressors with impluse-type bladings and constant tip diameters. Computing programs for Monroe-1800 programmable calculators are presented to establish the compressor performance and the blading parameters for arbitrary conditions with minimum effort.

The report was prepared to permit evaluations of the applicability of such compressors in advanced propulsions units for air-superiority aircraft, or in light-weight lift engines for military VTOL aircraft.

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CALCULATING METHOD FOR MULTI-STAGE
AXIAL COMPRESSORS WITH IMPULSE
BLADINGS AND CONSTANT TIP DIAMETER

by

M. H. Vavra

1. INTRODUCTION

Impulse-type stages of the type shown in Figs. 1 and 2 are presently used for fan stages of by-pass jet engines. Considerable progress has been made in their performance at supersonic Mach numbers of the relative inlet velocity W_1 . Reference 1 shows that at a tip Mach number of 1.43 it was possible to obtain rotor efficiencies close to 90 percent for total pressure ratios of the rotor of 1.7.

Second generation propulsion units for air-superiority Navy aircraft of the F-14 type will require overall pressure ratios of 30 and higher to produce the desired thrusts with acceptable fuel consumption, without increasing the diameter of the presently installed engines. To save weight it is imperative that compressors are available which can produce high pressure ratios with as few stages as possible. It is necessary, on the other hand, that their efficiencies are as high as or better than those of existing compressors. The possibility exists that compressors of the type considered can satisfy these requirements.

Multi-stage impulse-type compressors at elevated Mach numbers with high pressure ratios and efficiency could also be used in so-called lift engines for VTOL aircraft which must have very large thrust/weight ratios.

In a previous report (Ref. 2) a calculating procedure has been established for the performance evaluation of engines for air-superiority aircraft. With

1. Gostelow, J. P., "Design and Performance Evaluation of Four Transonic Compressor Rotors", ASME, Journal of Engineering for Power, January 1971, pp. 3/41.

Ref. 2 it will be possible to arrive at typical compressor specifications for the two applications with systematic changes of the various design parameters. The present report will then be used to calculate the dimensions and design particulars of suitable impulse-type compressors, and show what areas of ignorance must be clarified to reach the full potential of this type of compressor.

The ultimate purpose of the whole study is to examine whether research and development work in multi-stage impulse-type compressors is warranted, and if so, whether the facilities of the Propulsion Laboratory of the Naval Postgraduate School would be suitable for this endeavor. The results obtained by the study would then form the basis for a research program with well defined goals for particular compressors for specific Naval applications.

2. GENERAL CONCEPTS AND ASSUMPTIONS

The presented calculating method for multi-stage impulse-type compressor is limited to designs where all stages have the same outer diameter, and where the axial through-flow velocities of a stage vary from inlet to discharge. In particular, with the symbols of Fig. 3,

$$\frac{V_{a2}}{V_{a1}} = \frac{V_{a3}}{V_{a2}} = \lambda \quad (1)$$

where λ is smaller than unity to produce low axial velocities after the last compressor stage.

The principal variable parameters of impulse bladings are the relative tip flow angle β_{1T} , the rotor tip diffusion factor D_{RT} , the cascade solidity σ_{RT} at the rotor tip, and the peripheral rotor tip speed U_T . The total-to

2. Vavra, M. H., "Calculating Procedure of Sea-Level-Static Performance of Two-Spool Afterburning Bypass Jet Engine", Tech. Report NPS-57Va73061A, Naval Postgraduate School, Monterey, June 1973.

total stage efficiency is primarily a function of D_{RT} and the tip Mach number, although with small blade aspect ratios, as they occur in the later stages, the efficiency is also affected by tip clearance and end losses. These conditions will be taken into account in selecting appropriate values of the stage efficiencies, although it is not intended to support the chosen quantities by currently available loss evaluation methods which are at best approximate, and do not take into consideration the improvements that will be possible by future research efforts.

A calculating program for a Monroe 1880-22 programmable calculator has been set up to establish optimum solutions for particular design point conditions with minimum effort. The program consists of two parts. The first part (Program VA 511) calculates the compressor performance based on the tip conditions of the bladings, and determines the hub radii R_{h1} and R_{h3} of each stage for a specified hub/tip radius ratio of the first stage. These ratios are obtained by assuming that the axial velocity components V_{a1} and V_{a3} of Fig. 3 do not vary in the radial direction. It is assumed further that the flow through a stage has cylindrical stream surfaces and that along them the rotor has equal work input. Such conditions cannot exist in actuality because of the varying hub radii and because of curvature effects. It would also be more appropriate to design the rotors for equal total pressure ratios in radial direction than for equal work input. However, since this can be done only if the loss variation along the radius is known, the adopted method establishes only the general level of the work input per stage, without providing definite data for the design of the blading. To take account of the deterioration of the axial velocity profile in successive stages, a so-called work-done factor Ω is introduced, which is the ratio of the average work input for the actual velocity profile and that for a uniform velocity distribution. By introducing so-called

blockage factors k , the reduction of the actual annulus flow area by the displacement thickness of the wall boundary layers is accounted for in an overall manner.

The diffusion factors of the rotor and stator bladings between hub and tip are calculated in the second part of the program (Program VA 512) for specified changes of the blade chords c_R and c_S of Fig. 2. These data together with the respective flow angles and Mach numbers of the absolute and relative velocities, which are determined also, establish criteria to judge whether the blading is acceptable for the chosen tip conditions.

The calculations are carried out with dimensionless quantities and for arbitrary fluids, which are supposed to have constant specific heats. Consistent units are used throughout to facilitate conversion to other systems of dimensions. For instance in the equation of state

$$\rho = \frac{p}{R_G T} \quad (\text{slug/ft}^3) \quad (2)$$

the gas constant R_G in the English system of units is

$$R_G = \frac{g(1545.43)}{M} = \frac{49,722.66}{M} \left(\frac{\text{ft-lb}}{\text{slug, } ^\circ\text{R}} = \frac{\text{ft}^2}{\text{s}^2, ^\circ\text{R}} \right)$$

where M is the molecular weight of the gas. Further, the specific heat c_p equals

$$c_p = \frac{\gamma}{\gamma - 1} R_G \quad \left(\frac{\text{ft-lb}}{\text{slug, } ^\circ\text{R}} = \frac{\text{ft}^2}{\text{s}^2, ^\circ\text{R}} \right) \quad (3)$$

where $\gamma = c_p/c_v$. The velocity of sound a at the temperature T is then

$$a = \sqrt{\gamma R_G T} \quad (\text{ft/s}) \quad (4)$$

3. STAGE PERFORMANCE

If the velocity diagram of Fig. 3 pertains to the tip radius R_T of the blading of Fig. 1, the work input at the radius R_T is

$$\Delta H_T = U_T (\Delta W_u)_T \quad \Omega = \omega R_T (\Delta W_u)_T \Omega \quad \left(\frac{\text{ft-lb}}{\text{slug}} \right) \quad (5)$$

The subscript T is indicative of the tip conditions, Ω is the work-done factor, and ω the angular rotor velocity. At other radii $R = r R_T$, where $\Delta H = \Delta H_T$ by assumption,

$$\Delta H = \omega r R_T (\Delta W_u)_T \Omega = \Delta H_T$$

Hence, from Fig. 3 and with Eq. 5,

$$\omega R_T [V_{a1} \tan \beta_{1T} - \lambda V_{a1} \tan \beta_{2T}] = \omega R [V_{a1} \tan \beta_1 - \lambda V_{a1} \tan \beta_2]$$

or

$$\lambda \tan \beta_2 = \tan \beta_1 - \frac{1}{r} [\tan \beta_{1T} - \lambda \tan \beta_{2T}]$$

However, for constant axial velocity $V_1 = V_{a1}$ along the radius of the blading ahead of the rotor,

$$\tan \beta_1 = \frac{U}{V_{a1}} = r \frac{U_T}{V_{a1}} = r \tan \beta_{1T} \quad (6)$$

and

$$\tan \beta_2 = \frac{1}{\lambda} \left(r - \frac{1}{r} \right) \tan \beta_{1T} + \frac{1}{r} \tan \beta_{2T} \quad (7)$$

From Eqs. A(2) and A(3) of Appendix A the angle β_{2T} is obtained for given angles β_{1T} and chosen values of λ , σ_{RT} and D_{RT} . With

$$X_T = \frac{\sin \beta_{1T} + 2 \sigma_{RT} (1 - D_{RT})}{\lambda \cos \beta_{1T}} \quad (8)$$

there is

$$\sin \beta_{2T} = - \frac{2 \sigma_{RT}}{X_T^2 + 1} + \sqrt{\frac{X_T^2 - 4 \sigma_{RT}^2}{X_T^2 + 1} + \left(\frac{2 \sigma_{RT}}{X_T^2 + 1} \right)^2} \quad (9)$$

The diffusion factor D_R at a radius $R = r R_T$ is, by Eq. A(1), with Eqs. 6 and 7

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{\frac{1}{r}(\tan \beta_{1T} - \lambda \tan \beta_{2T})}{2 \sigma_R} \cos \beta_1$$

From Eq. A(2) for the tip conditions

$$Y_T \equiv \frac{1}{2}(\tan \beta_{1T} - \lambda \tan \beta_{2T}) = \left(D_{RT} + \lambda \frac{\cos \beta_{1T}}{\cos \beta_{2T}} - 1 \right) \frac{\sigma_{RT}}{\cos \beta_{1T}} \quad (10)$$

and

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{1}{r} \frac{\cos \beta_1}{\sigma_R} Y_T \quad (11)$$

The diffusion factor D_s of the stator blading is defined by

$$D_s = 1 - \frac{V_3}{V_2} + \frac{\Delta V_u}{2 \sigma_s V_2}$$

or, by Fig. 3 and Eq. 1,

$$D_s = 1 - \lambda \cos \alpha_2 + \sin \alpha_2 \frac{1}{2 \sigma_s} \quad (12)$$

Also

$$\tan \alpha_2 = \frac{\Delta V_u}{V_{a2}} = \frac{\Delta W_u}{\lambda V_{a1}} = \frac{V_{a1} \tan \beta_1 - \lambda V_{a1} \tan \beta_2}{\lambda V_{a1}}$$

With Eqs. 6, 7 and 10

$$\tan \alpha_2 = \frac{1}{r} \left(\frac{\tan \beta_{1T}}{\lambda} - \tan \beta_{2T} \right) = \frac{2 Y_T}{\lambda r} \quad (13)$$

From this relation the angle α_2 is obtained at different radius ratios r which, introduced in Eq. 12, establishes the stator diffusion factor along the radius.

For a gas with $c_p = \text{constant}$, and for an adiabatic process, from Eq. 5 and Fig. 4

$$\Delta T_w = T_{t3} = T_{t1} = \frac{\Delta H_T}{c_p} = \frac{U_T (\Delta W_u)_T}{c_p} \Omega = \frac{U_T^2}{c_p} \frac{(\Delta W_u)_T}{U_T} \Omega$$

The total temperature T_{t1} at the inlet of the first stage is denoted by T_0

and the total pressure P_{t1} at this location is called P_0 . Then

$$\frac{\Delta T_w}{T_0} = \frac{T_{t1}}{T_0} \left(\frac{T_{t3}}{T_{t1}} - 1 \right) = \frac{U_T^2}{c_p T_0} \Omega \left(1 - \lambda \frac{\tan \beta_{2T}}{\tan \beta_{1T}} \right) \quad (14)$$

The dimensionless quantity $U_T / \sqrt{c_p T_0}$ is denoted by N_u , or, with Eq. 3,

$$N_u = \frac{U_T}{\sqrt{c_p T_0}} = \frac{U_T}{\sqrt{\frac{\gamma}{\gamma-1} R_G T_0}} \quad (15)$$

Then

$$\frac{\Delta T_w}{T_0} = N_u^2 \Omega \left(1 - \lambda \frac{\tan \beta_{2T}}{\tan \beta_{1T}} \right) \quad (16)$$

and

$$\frac{T_{t3}}{T_0} = \frac{T_{t1}}{T_0} + \frac{\Delta T_w}{T_0} \quad (17)$$

The stage efficiency η_S is defined as

$$\eta_S = \frac{\Delta T_{is}}{\Delta T_w}$$

where, according to Fig. 4, the quantity ΔT_{is} is the temperature difference $T'_{t3} - T_{t1}$, proportional to the work necessary to produce a pressure ratio P_{t3}/P_{t1} with an isentropic process. Thus

$$\frac{T'_{t3}}{T_{t1}} = \left(\frac{P_{t3}}{P_{t1}} \right)^{\frac{\gamma}{\gamma-1}} = 1 + \frac{\Delta T_w}{T_{t1}} \eta_S = 1 + \frac{\Delta T_w}{T_0} \left(\frac{T_{t1}}{T_0} \right) \eta_S$$

Thus

$$\frac{P_{t3}}{P_{t1}} = \left(1 + \frac{\Delta T_w}{T_0} \left(\frac{T_{t1}}{T_0} \right) \eta_S \right)^{\frac{\gamma}{\gamma-1}} \quad (18)$$

and

$$\frac{P_{t3}}{P_0} = \frac{P_{t3}}{P_{t1}} \frac{P_{t1}}{P_0} \quad (19)$$

4. CONDITIONS OF STATE IN STAGE

As shown in Fig. 4, the static temperature T_1 at station (1) ahead of the rotor is obtained from

$$T_1 = T_{t1} - \frac{V_1^2}{2 \text{ cp}} = T_{t1} - \frac{V_{a1}^2}{2 \text{ cp}} = T_{t1} - \frac{U_T^2 \cot^2 \beta_{1T}}{2 \text{ cp}}$$

T_1 is equal at all radii since V_{a1} is assumed to be constant at station (1).

With Eq. 15

$$\frac{T_1}{T_{t1}} = 1 - \frac{N_u^2}{2} \frac{1}{T_{t1}/T_0} \cot^2 \beta_{1T} \quad (20)$$

or

$$\frac{T_1}{T_0} = T_{t1}/T_0 - \frac{N_u^2}{2} \cot^2 \beta_{1T} \quad (21)$$

The static pressure p_1 at station (1) is given by

$$\frac{p_1}{P_{t1}} = \left(\frac{T_1}{T_{t1}} \right)^{\frac{\gamma}{\gamma - 1}}$$

and

$$\frac{p_1}{P_0} = \frac{p_1}{P_{t1}} \frac{P_{t1}}{P_0} \quad (22)$$

The mass density $\rho_1 = p_1/(R_G T_1)$ is

$$\frac{\rho_1}{\rho_0} = \frac{p_1/P_0}{T_1/T_0} \quad (23)$$

where

$$\rho_0 = \frac{P_0}{R_G T_0} \quad (24)$$

By Fig. 4 and Eq. 1 the static temperature after the rotor is, with

$$T_{t2} = T_{t3},$$

$$T_2 = T_{t3} - \frac{V_2^2}{2 \text{ cp}} = T_{t3} - \frac{\lambda^2 V_{a1}^2}{\cos^2 \alpha_2} \frac{1}{2 \text{ cp}}$$

Also

$$\frac{T_2}{T_0} = \frac{T_{t3}}{T_0} - \frac{\lambda^2 N_u^2 \cot^2 \beta_{1T}}{2 \cos^2 \alpha_2} \quad (25)$$

with T_{t3}/T_0 from Eq. 17. It must be noted that the angle α_2 changes along the radius. For different radius ratios r , the angle α_2 is obtained from Eq. 13.

Because only the overall stage efficiency η_s will be chosen, and not the rotor and stator efficiencies separately, the static pressure p_2 , which varies along R also, cannot be determined with the present analysis. For this reason it is also not possible to evaluate the density ρ_2 at station (2).

From

$$T_3 = T_{t3} - \frac{V_3^2}{2 \text{ cp}} = T_{t3} - \frac{V_{a3}^2}{2 \text{ cp}}$$

in accordance with Fig. 4, and since by Eq. 1, $V_{a3} = \lambda^2 V_{a1}$,

$$\frac{T_3}{T_{t3}} = 1 - \frac{\lambda^4 N_u^2}{2} \frac{1}{(T_{t3}/T_0)} \cot^2 \beta_{1T} \quad (26)$$

and

$$\frac{T_3}{T_0} = \frac{T_{t3}}{T_0} - \frac{\lambda^4 N_u^2}{2} \cot^2 \beta_{1T} \quad (27)$$

where T_{t3}/T_0 is known from Eq. 17. Because $V_3 = V_{a3}$ is assumed to be constant at station (3) the temperature T_3 is constant also, and the static pressure p_3 can be determined from

$$\frac{p_3}{p_{t3}} = \left(\frac{T_3}{T_{t3}} \right)^{\frac{\gamma}{\gamma-1}} \quad (28)$$

or

$$\frac{p_3}{p_0} = \frac{p_3}{p_{t3}} \frac{p_{t3}}{p_0} \quad (29)$$

The mass density ρ_3 at station (3) is then, with Eq. 24,

$$\frac{\rho_3}{\rho_0} = \frac{p_3/p_0}{T_3/T_0} \quad (30)$$

5. HUB DIMENSIONS OF STAGE

The hub/tip ratio $r_1 = R_{h1}/R_T$ at station (1) of the first stage will be chosen, and is denoted by $(r_1)_I$. At this station there is $p_{t1} = p_0$ and $T_{t1} = T_0$. With a blockage factor $(k_1)_I$ the mass flow rate $\dot{m}$ is

$$\dot{m} = \pi R_T^2 \left[1 - (r_1)_I^2 \right] (V_{a1})_I (p_1)_I (k_1)_I \quad (\text{slug/s})$$

With Eq. 15, $V_{a1} = U_T \cot \beta_{1T}$, and Eqs. 24 and 22,

$$\dot{m} = \pi R_T^2 \left[1 - (r_1)_I^2 \right] N_u \sqrt{\frac{\gamma}{\gamma-1} R_G T_0} \cot(\beta_{1T})_I \left[1 - \frac{N_u^2}{2} \cot^2(\beta_{1T})_I \right]^{\frac{1}{\gamma-1}} \rho_0 (k_1)_I$$

with ρ_0 from Eq. 24.

With the so-called referred dimensionless mass flow rate $\dot{m}_{REF}$

$$\dot{m}_{REF} \equiv \frac{\dot{m} \sqrt{\frac{\gamma-1}{\gamma} R_G T_0}}{\pi R_T^2 p_0} = \frac{\dot{m} \left(\frac{\gamma-1}{\gamma} \right) \sqrt{c_p T_0}}{\pi R_T^2 p_0} \quad (31)$$

there is also

$$\dot{m}_{REF} = \left[1 - (r_1)_I^2 \right] N_u \cot(\beta_{1T})_I \left[1 - \frac{N_u^2}{2} \cot^2(\beta_{1T})_I \right]^{\frac{1}{\gamma-1}} (k_1)_I \quad (32)$$

The angle $(\beta_{1T})_I$ is the relative inlet flow angle at the tip of the rotor of the first stage. Hence the quantity $\dot{m}_{REF}$ of Eq. 29 is determined by the chosen conditions at the inlet to the first stage.

At stations (1) of the other stages, there is

$$\dot{m} = \pi R_T^2 [1 - r_1^2] N_u \cot \beta_{1T} \frac{\rho_1}{\rho_0} \frac{P_0}{R_G T_0} k_1 \sqrt{\frac{\gamma}{\gamma - 1} R_G T_0} \quad (33)$$

or, with Eq. 31

$$r_1 = \left[1 - \frac{\dot{m}_{REF}/k_1}{N_u \cot \beta_{1T} (\rho_1/\rho_0)} \right]^{\frac{1}{2}} \quad (34)$$

The density ratio ρ_1/ρ_0 is known from Eq. 23.

At stations (3) of the stages, with $V_{a3} = \lambda^2 V_{a1}$ and the blockage factor k_3 , the radius ratio $r_3 = R_{h3}/R_T$ is obtained from

$$r_3 = \left[1 - \frac{\dot{m}_{REF}/k_3}{\lambda^2 N_u \cot \beta_{1T} (\rho_3/\rho_0)} \right]^{\frac{1}{2}} \quad (35)$$

with ρ_3/ρ_0 from Eq. 30.

6. MACH NUMBERS OF STAGE VELOCITIES

At station (1) of a stage the velocity $V_1 = V_{a1}$ is constant. The relative velocities W_1 along the radius are

$$W_1 = \frac{V_1}{\cos \beta_1}$$

where β_1 for different radius ratios r is obtained from Eq. 6. Thus if the Mach number M_{V1} of the velocity V_1 is known there is

$$M_{W1} = \frac{W_1}{a_1} = \frac{V_1}{a_1} \frac{1}{\cos \beta_1} = M_{V1} \frac{1}{\cos \beta_1} \quad (36)$$

From Eqs. 4, 3, and 15 and $V_1 = U_T \cot \beta_{1T}$

$$M_{V1} = \frac{U_T \cot \beta_{1T}}{\sqrt{\gamma R_G T_1}} = \frac{N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\sqrt{T_1/T_0}} \quad (37)$$

The temperature ratio T_1/T_0 is given by Eq. 21.

At station (2) the absolute velocity V_2 varies along the radius, since $V_2 = V_{a2}/\cos \alpha_2$ with α_2 given by Eq. 13. Moreover $W_2 = V_{a2}/\cos \beta_2$, or

$$W_2 = V_2 \frac{\cos \alpha_2}{\cos \beta_2}$$

and the Mach number M_{W2} of W_2 is

$$M_{W2} = M_{V2} \frac{\cos \alpha_2}{\cos \beta_2} \quad (38)$$

The flow angle β_2 is obtained from Eq. 7 for different radius ratios r .

There is

$$M_{V2} = \frac{V_{a2}}{\cos \alpha_2 a_2} = \frac{\lambda V_{a1}}{\cos \alpha_2 a_2} = \frac{\lambda U_T \cot \beta_{1T}}{\cos \alpha_2 \sqrt{\gamma R_G T_2}}$$

With Eq. 15

$$M_{V2} = \frac{\lambda N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\cos \alpha_2} \frac{1}{\sqrt{T_2/T_0}} \quad (39)$$

with T_2/T_0 from Eq. 25.

At station (3) the velocity V_3 and the temperature T_3 are constant. With $V_3 = \lambda^2 V_{a1}$ there is

$$M_{V3} = \frac{V_3}{a_3} = \frac{\lambda^2 N_u}{\sqrt{\gamma - 1}} \frac{\cot \beta_{1T}}{\sqrt{T_3/T_0}} \quad (40)$$

where T_3/T_0 is known from Eq. 27.

7. STAGE-BY-STAGE CALCULATIONS (PROGRAM VA 511)

The following data have to be assumed for a particular design:

M = molecular weight of gas

γ = specific heat ratio of gas

$(\beta_{1T})_I$ = relative flow angle at tip of first-stage rotor

$(r_1)_I$ = hub/tip ratio at inlet of first-stage rotor

$(k_1)_I$ = blockage factor at inlet of first-stage

$N_u = U_T / \sqrt{c_p T_0}$ = dimensionless tip speed

The quantities listed below must be chosen for each stage J from $J = I$ to $J = J_{\max}$:

$(D_{RT})_J$ = diffusion factor at rotor tip

$(\sigma_{RT})_J$ = solidity at rotor tip

$\lambda_J = (V_{a2}/V_{a1})_J = (V_{a3}/V_{a2})_J$ = axial velocity ratio

Ω_J = work-done factor

$(\eta_s)_J$ = total-to-total stage efficiency

$(k_3)_J$ = blockage factor at stage exit

For $J = I$ these values determine the referred mass flow rate $\dot{m}_{REF}$ of Eq.

32. With $(\beta_{1T})_I$, $(D_{RT})_I$, λ_I , the angle $(\beta_{2T})_I$ is obtained from Eqs. 8 and 9. Equations 16 and 17 establish $(T_{t3}/T_0)_I$ for $(T_{t1}/T_0)_I = 1$. The total pressure ratio $(P_{t3}/P_{t1})_I = (P_{t3}/P_0)_I$ is obtained from Eqs. 16 and 18. The density ratio $(\rho_3/\rho_0)_I$ can now be calculated from Eq. 30 to establish the ratio $(r_3)_I$ by means of Eq. 35.

For each stage from $J = II$ to $J_{\max}$ the above-listed procedure must be carried out also, but the relative rotor tip angle $(\beta_{1T})_J$ must be determined from

$$(\tan \beta_{1T})_J = \frac{(\tan \beta_{1T})_J - 1}{(\lambda_J - 1)^2} \quad (41)$$

Equation 41 is obtained because the axial velocity $V_3 = V_{a3}$ after a stage, which is V_{a1} of the next stage, equals $\lambda^2 V_{a1}$ and since $\tan \beta_{1T} = U_T/V_{a1}$.

Moreover,

$$\left(\frac{T_{t1}}{T_0}\right)_J = \left(\frac{T_{t3}}{T_0}\right)_{J-1}$$

and

$$\left(\frac{P_{t1}}{P_0}\right)_J = \left(\frac{P_{t3}}{P_0}\right)_{J-1}$$

After the last stage $J_{\max}$ has been processed, the ratios

$$\left(\frac{P_{t3}}{P_0}\right)_{J_{\max}} = \left(\frac{P_{t3}}{P_0}\right)_d \quad (42)$$

and

$$\left(\frac{T_{t3}}{T_0}\right)_{J_{\max}} = \left(\frac{T_{t3}}{T_0}\right)_d \quad (43)$$

establish the overall total-to-total compressor efficiency η_c from

$$\eta_c = \frac{\left(\frac{P_{t3}}{P_0}\right)_d^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{T_{t3}}{T_0}\right)_d - 1} \quad (44)$$

For a chosen tip radius R_T and values of T_0 and P_0 the mass flow rate of the compressor is from Eq. 31

$$\dot{m} = \dot{m}_{\text{REF}} \frac{\pi R_T^2 P_0}{\sqrt{\left(\frac{\gamma-1}{\gamma}\right) R_G T_0}} \quad (\text{slug/s}) \quad (45)$$

With R_T in inches, P_0 in psia, T_0 in $^{\circ}\text{R}$, and R_G in $(\text{ft-lb})/(\text{slug}, ^{\circ}\text{R})$, the flow rate is obtained in slug/s. Dividing $\dot{m}$ by $g = 32.174 \text{ ft/s}^2$ gives the weight flow rate $\dot{w}$ in lbm/s.

The necessary driving power of the compressor in HP, exclusive of mechanical losses, equals

$$\text{HP} = \dot{m} c_p T_0 \left[\left(\frac{T_{t3}}{T_0}\right)_d - 1 \right] \frac{1}{550} \quad (46)$$

From Eq. 15 the blade tip speed U_T is

$$U_T = N_u \sqrt{c_p T_0} \quad (\text{ft/s})$$

and the rotative speed N of the compressor equals

$$N = \frac{U_T 360}{\pi R_T} \quad (\text{rpm})$$

for R_T in inches.

The above-listed calculations can be performed with calculating program VA 511 on a programmable Monroe Calculator Model 1880-22. The operating instructions are given in Appendix B with a complete listing of the program steps. After a particular stage has been processed the stage data are printed by the calculator. These strips can be attached to Tables D-1 of Appendix B. After all stages have been calculated the overall compressor performance is printed. For easy identification, these paper strips can be attached to the lower half of Tables D-2 of Appendix D. Together with the print-outs at the start of the program, affixed to the upper portion of Table D-2, all pertinent overall compressor data are then listed in Table D-2 for particular configurations and assumptions.

After the printing of the individual stage data, these values must be written on one-half of a magnetic card (32 registers, starting at register 50) for use in program VA 512 to determine the particulars of the blading.

8. BLADING CALCULATIONS (PROGRAM VA 512)

This program handles each stage of the compressor separately. The data of a particular stage are transferred from program VA 511 to program VA 512 by means of magnetic cards.

The rotor blading is investigated first. These calculations are started by choosing the diffusion factor D_{Rh} at the hub at the rotor blading which is considered to be at the inner radius ratio r_1 at the rotor inlet. The

diffusion factor D_{RT} is known from the preceding calculations. Then by Eq. A(1) of Appendix A the rotor blade solidity σ_{Rh} at r_1 is

$$\sigma_{Rh} = \frac{\tan \beta_{1h} - \lambda \tan \beta_{2h}}{2 \left[\frac{\lambda}{\cos \beta_{2h}} - \frac{1 - D_{Rh}}{\cos \beta_{1h}} \right]} \quad (47)$$

The angles β_{1h} and β_{2h} are obtained from Eqs. 6 and 7, for $r = r_1$.

It will be assumed that the rotor blade chord varies linearly from c_{Rh} to c_{Rt} between r_1 and $r = 1$. Then at the radius ratios r between r_1 and unity,

$$c_R = c_{RT} - (c_{RT} - c_{Rh}) \frac{1 - r}{1 - r_1}$$

The blade spacing s_R is

$$s_R = s_{RT} \quad r = s_{Rh} \frac{r}{r_1}$$

Thus the solidity σ_R at the radius ratio r equals

$$\sigma_R = \frac{1}{r} \left[\sigma_{RT} - (\sigma_{RT} - r_1 \sigma_{Rh}) \frac{1 - r}{1 - r_1} \right] \quad (48)$$

The rotor blade diffusion factor D_R at the radius r can then be calculated by Eq. 11, with the angles β_1 and β_2 from Eqs. 6 and 7. These data are determined at two radius ratios between hub and tip, namely, at

$$r = r_1' = 1/3(1 + 2r_1) \quad (49)$$

and

$$r = r_1'' = 1/3(2 + r_1) \quad (50)$$

which correspond to stations at 1/3 and 2/3 of the blade height at the rotor inlet.

Equations 36 and 37 will be used to determine the Mach numbers of the relative velocities at the hub, tip and the intermediate radius ratios r_1'

and r_1'' . Although the radius ratio r_2 at the hub after the rotor is larger than r_1 , the flow angles and Mach numbers of the relative velocities W_2 after the rotor will be determined as if r_2 were equal to r_1 ; that is, at the radius ratios r_1 , r_1' , r_1'' and unity. These values are obtained with Eqs. 7, 13, 38, and 39.

The stator blading is treated as if the radius ratio r_2 were equal to r_3 . The angle α_{2h} for $r = r_3$ is determined first with Eq. 12 for $r = r_3$. Then, a diffusion factor $D_S = D_{Sh}$ is chosen at $R_{3h} = r_3 R_T$, which establishes the solidity σ_{Sh} with Eq. 12 or from

$$\sigma_S = \frac{\sin \alpha_2}{2[\lambda \cos \alpha_2 - (1 - D_S)]} \quad (51)$$

if $\alpha_2 = \alpha_{2h}$ and $D_S = D_{Sh}$. In the same manner the solidity σ_{ST} at the outer radius of the stator is established for a chosen diffusion factor D_{ST} at $r = 1$. Then at two radius ratios, namely,

$$r = r_3' = 1/3(1 + 2r_3)$$

and

$$r = r_3'' = 1/3(2 + r_3)$$

which are at $1/3$ and $2/3$ of the stator blade height, the solidity is obtained with a relation similar to Eq. 48, or

$$\sigma_S = \frac{1}{r} \left[\sigma_{ST} - (\sigma_{ST} - r_3 \sigma_{Sh}) \frac{1 - r}{1 - r_3} \right]$$

by assuming a liner change of the stator blade chord between hub and tip.

The diffusion factor D_S at r can now be calculated by Eq. 12.

The data so established are used to determine the Mach numbers M_{V2} and M_{V3} of the absolute velocities ahead of and after the stator blades by means of Eqs. 39 and 40.

The operating instructions of program VA 512 are given in Appendix C, together with a listing of the calculating steps. Although the program can be loaded at any Branch Point, the Program Counts (P-Ct) of the operating instructions only hold for loading at Branch Point 00. At P-Ct 0014 the diffusion factor D_{Rh} of the rotor blading at the hub must be chosen. After the print-out of D_{Rh} and the corresponding calculated hub solidity σ_{Rh} , a decision must be made at P-Ct 0021 whether σ_{Rh} is acceptable for the selected tip solidity σ_{RT} of program VA 511. Entering "0" on the keyboard and depressing the (RESUME) key returns the program to P-Ct 0014 where an improved values of D_{Rh} can be introduced to obtain a better value of σ_{Rh} . This process can be repeated as often as necessary. If the best possible solidity σ_{Rh} has been obtained, the program exits the ($D_{Rh} \rightarrow \sigma_{Rh}$) loop if the (RESUME) key is depressed without entering "0" at P-Ct 0021. The last value of D_{Rh} which was introduced, and the corresponding solidity σ_{Rh} are then used to calculate and print the rotor blade data at the hub, the one-third and two-thirds blade heights, and at the tip. At the next stop of the program (P-Ct 0091), the paper tape can be removed and attached to the left-hand side of Table D-3 of Appendix D for ease of identification of the calculated values.

At the same P-Ct (0091), the diffusion factor D_{Sh} at the hub of the stator blade must be introduced before depressing the (RESUME) key. This value and the calculated hub solidity σ_{Sh} for D_{Sh} are printed out at P-Ct 0121. If the hub solidity σ_{Sh} has to be changed, the program can be returned to P-Ct 0091 by entering "0" on the keyboard and depressing the (RESUME) key. Depressing the (RESUME) key only, exits the program from the ($D_{Rh} \rightarrow \sigma_{Rh}$) loop, and stops the program at P-Ct 0131. At this stop a chosen value of the diffusion factor D_{ST} of the stator blading at the tip; that is, at the outer radius R_T , must be introduced before the (RESUME) key is depressed

again. The chosen D_{ST} and the corresponding stator tip solidity σ_{ST} are printed out at P-Ct 0154. By entering "0" on the keyboard and depressing the (RESUME) key this value can be modified by introducing other quantities D_{ST} at P-Ct 0131. It is possible, however, that in view of the finally chosen hub diffusion factor D_{Sh} and/or the resulting blading hub solidity σ_{Sh} of the preceeding loop, the best possible solidity σ_{ST} obtained with the $(D_{ST} \rightarrow \sigma_{ST})$ loop does not produce an acceptable stator blading. In this case it is possible to jump from P-Ct 0154 to P-Ct 0099 by entering "-1" on the keyboard and depressing the (RESUME) key, to choose a more favorable hub diffusion factor D_{Sh} and a better solidity σ_{Sh} at the stator blade hub. If then the $(D_{ST} \rightarrow \sigma_{ST})$ loop produces an acceptable tip solidity σ_{ST} also, the (RESUME) key must be depressed at P-Ct 154 without entering either "0" or "-1" on the keyboard. During the following operation the calculator establishes and prints the stator blade data at the hub, the one-third and the two-thirds blade heights, and at the tip. The paper strip of this data can be removed at P-Ct 0208 and should be attached to the right-hand side of Table D-3 of Appendix D to identify the calculated numbers.

To process the blading data of another stage the keyboard instructions JUMP(()), 0, 0, (RESUME), must be entered at P-Ct 0208 to re-route the program to P-Ct 0003 where the magnetic card with the particulars of that stage must be read into the calculator.

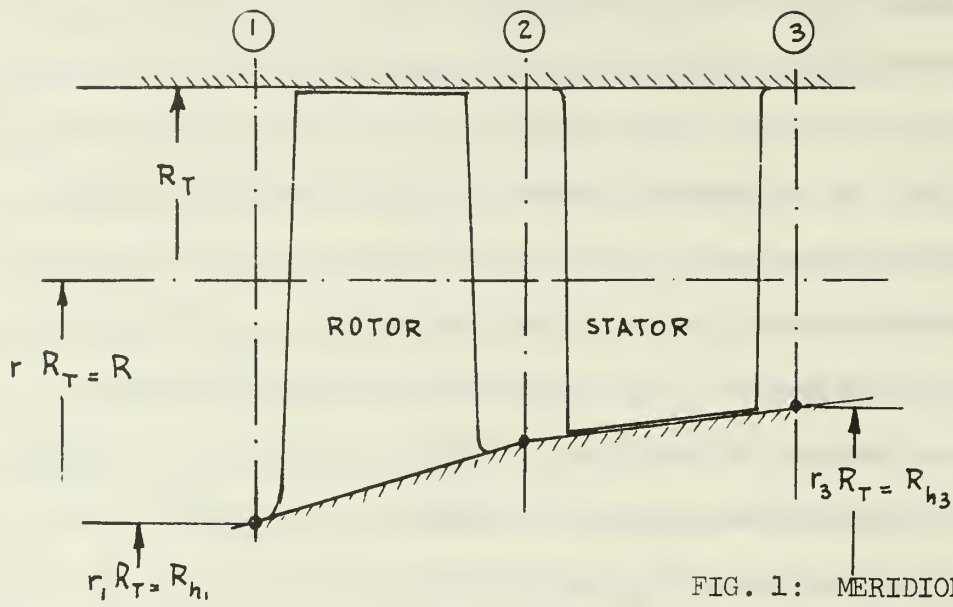


FIG. 1: MERIDIONAL CHANNEL OF IMPULSE STAGE

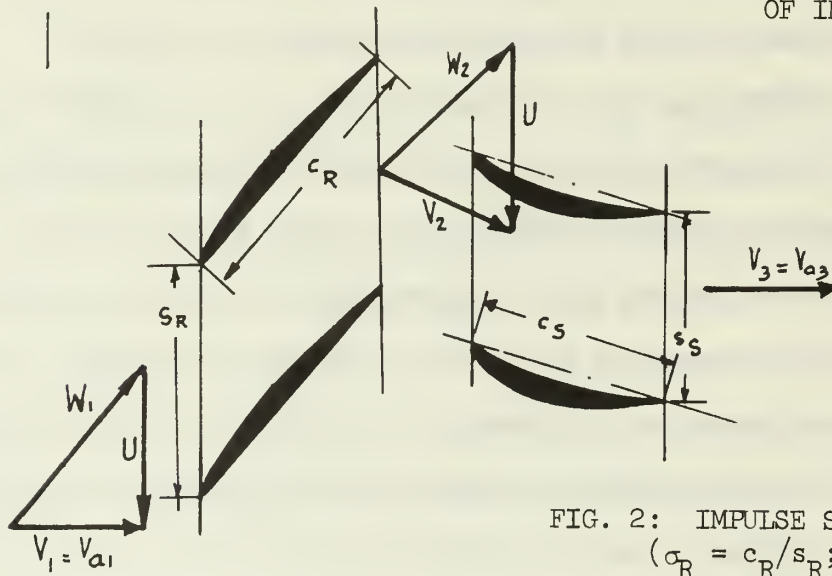


FIG. 2: IMPULSE STAGE BLADING
($\sigma_R = c_R/s_R$; $\sigma_S = c_S/s_S$)

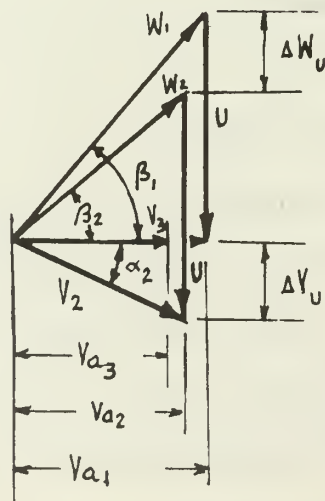


FIG. 3: VELOCITY DIAGRAM OF IMPULSE BLADING

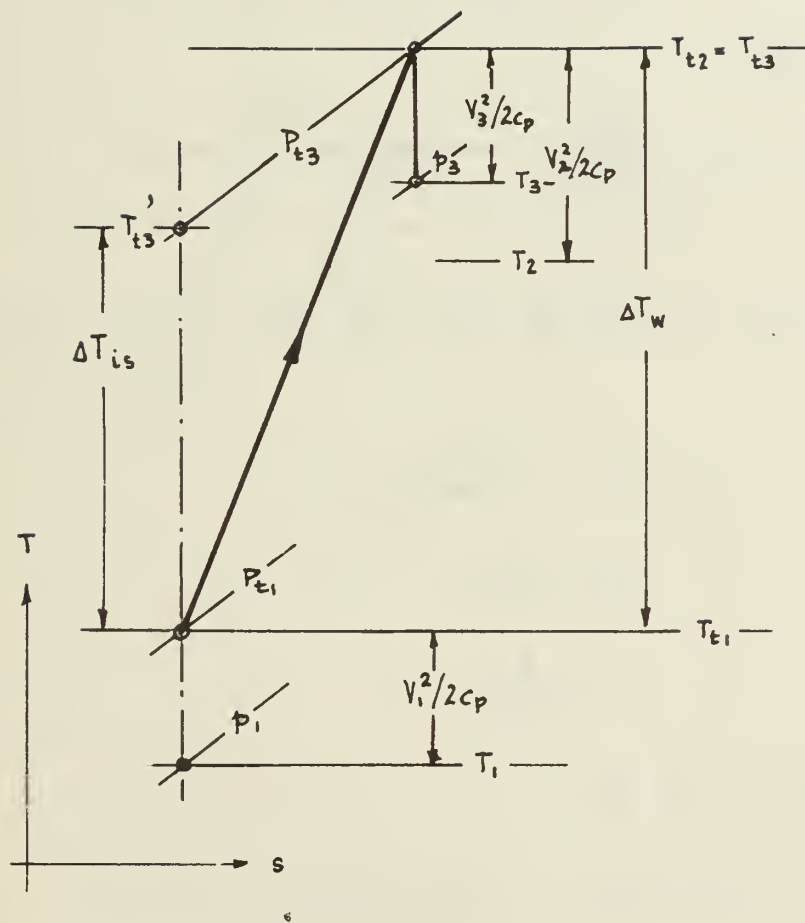


FIG. 4: COMPRESSION PROCESS OF STAGE
IN ENTROPY DIAGRAM

T_t = Total Temperature

T = Static Temperature

P_t = Total Pressure

p = Static Pressure

APPENDIX A: FLOW DEFLECTION FOR GIVEN INLET ANGLE
SPECIFIED DIFFUSION FACTOR, AND AXIAL VELOCITY RATIO

With the symbols of Fig. 1 the rotor diffusion factor D_R is defined by

$$D_R = 1 - \frac{W_2}{W_1} + \frac{\Delta W_u}{2 \sigma_R W_1}$$

With $V_{a2} = \lambda V_{a1}$

$$D_R = 1 - \lambda \frac{\cos \beta_1}{\cos \beta_2} + \frac{\tan \beta_1 - \lambda \tan \beta_2}{2 \sigma_R} \cos \beta_1 \quad A(1)$$

Rewritten

$$A \cos \beta_2 = B + C \sin \beta_2$$

where

$$A = 1 + \frac{\sin \beta_1}{2 \sigma_R} - D_R$$

$$B = \lambda \cos \beta_1$$

$$C = \frac{B}{2 \sigma_R}$$

With $\cos^2 \beta_2 = 1 - \sin^2 \beta_2$,

$$A^2(1 - \sin^2 \beta_2) = B^2 + 2BC \sin \beta_2 + C^2 \sin^2 \beta_2$$

and

$$\sin \beta_2 = - \frac{BC}{A^2 + C^2} \pm \sqrt{\frac{A^2 - B^2}{A^2 + C^2} + \left(\frac{BC}{A^2 + C^2} \right)^2}$$

There are:

$$\frac{BC}{A^2 + C^2} = \frac{B^2}{2 \sigma_R} \frac{1}{A^2 + \frac{B^2}{4 \sigma_R}} = \frac{2 \sigma_R}{4 \sigma_R^2 \left(\frac{A}{B} \right)^2 + 1}$$

$$\frac{A^2 - B^2}{A^2 + C^2} = \frac{\left(\frac{A}{B}\right)^2 - 1}{\left(\frac{A}{B}\right)^2 + \frac{1}{4 \sigma_R^2}} = \frac{4 \sigma_R^2 \left(\frac{A}{B}\right)^2 - 4 \sigma_R^2}{4 \sigma_R^2 \left(\frac{A}{B}\right)^2 + 1}$$

Let

$$X = 2 \sigma_R \frac{A}{B} = \frac{\sin \beta_1 + 2 \sigma_R (1 - D_R)}{\lambda \cos \beta_1} \quad A(2)$$

Then

$$\sin \beta_2 = -\frac{2 \sigma_R}{X^2 + 1} + \sqrt{\frac{X^2 - 4 \sigma_R^2}{X^2 + 1} + \left(\frac{2 \sigma_R}{X^2 + 1}\right)^2} \quad A(3)$$

Hence for known values of β_1 , σ_R , λ , and D_R the flow angle β_2 is obtained from Eqs. A(2) and A(3).

APPENDIX B: PROGRAM VA 511 FOR
MONROE 1880-22 PROGRAMMABLE CALCULATOR

STAGE-BY-STAGE CALCULATIONS AND
OVER-ALL PERFORMANCE OF MULTI-STAGE
AXIAL COMPRESSOR WITH IMPULSE BLADINGS

OPERATING INSTRUCTIONS PROGRAM VA 511 (MONROE 1880-22 CALCULATOR)

MULTI-STAGE AXIAL COMPRESSOR WITH IMPULSE BLADING
(Set-Up: LOAD MAGNETIC CARDS OF PROGRAM AT BRANCH PT. 00; D.P. 4)

P-COUNT	ENTER	PRINT-OUT
0010	M	M
0017	γ	γ
0051	β_{1T}	 β_{1T}
0064	r_1	r_1
0072	k_1	k_1
0091	$N_u = \frac{U_T}{\sqrt{c_p T_0}}$	N_u
0206	D_{RT}	$\dot{m}_{REF}$
0211	σ_{RT}	
0221	λ	
0290	Ω	
0320	η_s	
0425	k_3	
0585	WRITE Stage Data on one side of Magnetic card with set-up: [↑()()] 50, WRITE	{ Data Stage J (see Table D-1)
	$(J + 1) \leq J_{max}$ $(J + 1) > J_{max}$	
	(RESUME)	ENTER: 0 (RESUME)
0670	ENTER: T_0 ($^{\circ}R$)	
0678	" : P_0 (psia)	
0688	" : $D_T = 2 R_T$ (inches)	{ Compressor Data (see Table D-2)
0838	HALT	

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0	0	4				
1		9				
2		7				
3		2				
4		2				
5		.				
6		6				
7		6	$\mathcal{R}$			
8		$\div$				
9		HALT	M	M		
1	0	PRINT X				M
1		x	R_g			
2		$\downarrow () ()$				
3		0				
4		0			$R_g \rightarrow 00$	
5		(				
6		HALT	γ	γ		
7		$\downarrow () ()$				
8		0				
9		1			$\gamma \rightarrow 01$	
2	0	PRINT X				γ
1		$\div$				
2		(				
3		$\uparrow () ()$				
4		0				
5		1	γ			
6		-				
7		1				
8		)	$\gamma-1$			
9		$\downarrow () ()$				
3	0	0				
1		2			$\gamma-1 \rightarrow 02$	
2		)	$\gamma/(\gamma-1)$			
3		$\downarrow () ()$				
4		0				
5		3			$\frac{\gamma}{\gamma-1} \rightarrow 03$	
6		=	C_p			
7		$\downarrow () ()$				
8		0				
9		4			$C_p \rightarrow 04$	
4	0	$\uparrow () ()$				
1		0				
2		2	$\gamma-1$			
3		INV	$\frac{1}{\gamma-1}$			
4		$\downarrow () ()$				
5		0				
6		5			$\frac{1}{\gamma-1} \rightarrow 05$	
7	ECODE	176	PRINT LINE OF DOTS			
8		SET D.P				
9		4				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
5	0	HALT	$(\beta_{1T})_I$	$(\beta_{1T})_I$		
	1	$\downarrow () ()$				
	2	8			$(\beta_{1T})_I \rightarrow 80$	
	3	0				
	4	PRINT X				$(\beta_{1T})_I$
	5	E CODE 073	$\tan(\beta_{1T})_I$			
	6	INV	$\cot(\beta_{1T})_I$			
	7	$\downarrow () ()$				
	8	0				
	9	8			$\cot(\beta_{1T})_I \rightarrow 08$	
6	0	1	1			
	1	-				
	2	(				
	3	HALT	$(r_1)_I$	$(r_1)_I$		
	4	$\downarrow () ()$				
	5	5				
	6	1			$(r_1)_I \rightarrow 51$	
	7	PRINT X				$(r_1)_I$
	8	X				
	9	)	$(r_1)_I^2$			
7	0	X	$1 - (r_1)_I^2$			
	1	HALT		$(k_1)_I$		
	2	PRINT X				$(k_1)_I$
	3	$\downarrow () ()$				
	4	5				
	5	7			$(k_1)_I \rightarrow 57$	
	6	X				
	7	$\uparrow () ()$				
	8	0				
	9	8	$\cot(\beta_{1T})_I$			
8	0	=	$b = (k_1)_I [1 - (r_1)_I^2] \cot(\beta_{1T})_I$			
	1	$\downarrow ()$				
	2	0			$b \rightarrow 0$	
	3	E CODE 176	PRINT LINE OF DOTS			
	4	$\uparrow () ()$				
	5	5				
	6	1	$(r_1)_I$			
	7	$\downarrow ()$				
	8	7			$(r_1)_I \rightarrow 7$	
	9					
9	0	HALT	N_u	N_u		
	1	$\downarrow () ()$				
	2	1				
	3	0			$N_u \rightarrow 10$	
	4	PRINT X				N_u
	5	X				
	6	$\uparrow () ()$				
	7	0				
	8	8	$\cot(\beta_{1T})_I$			
	9	X				

STEP	SUBSTEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
1	0	0	÷				
	1		2				
	2		CHSGN				
	3		+				
	4		1				
	5		a^x	$(T_1/T_0)_I = 1 - \frac{Nu^4}{2} \cot^2(\beta_{1,T})_I$			
	6		↓() ()				
	7		6				
	8		2				
	9		↑() ()				
							$(T_1/T_0)_I \rightarrow 62$
1	1	0	0				
	1		3	$\frac{\gamma}{\gamma-1}$			
	2		÷	$(p_1/p_0)_I$			
	3		↓() ()				
	4		6				
	5		3				
	6		↑() ()				
	7		6				
	8		2	$(T_1/T_0)_I$			
	9		x				
							$(p_1/p_0)_I \rightarrow 63$
1	2	0	↑()				
	1		0	b			
	2		x				
	3		↑() ()				
	4		1				
	5		0	Nu			
	6		=	$\dot{m}_{REF}$			
	7		↓() ()				
	8		1				
	9		1				
							$\dot{m}_{REF} \rightarrow 11$
1	3	0	PRINT A				$\dot{m}_{REF}$
	1	E CODE	176	PRINT 2 LINES OF DOTS			
	2	E CODE	176				
	3		1	1			
	4		↓() ()				
	5		8				
	6		1	$(\lambda/J-1 \text{ for } J=1=1)$			
	7		↓() ()				
	8		6				
	9		0	$(T_{t1}/T_0)_I = 1$			
							$1 \rightarrow 60$
1	4	0	↓() ()				
	1		6				
	2		1	$(P_{t1}/P_0)_I = 1$			
	3		↑() ()				
	4		0				
	5		3	$\gamma/(\gamma-1)$			
	6		INV	$(\gamma-1)/\gamma$			
	7		↓() ()				
	8		0				
	9		6				
							$\frac{\gamma-1}{\gamma} \rightarrow 06$

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
150		$\uparrow()()$				
1		0				
2		8	$\cot(\beta_{1T})I$			
3		INV	$\tan(\beta_{1T})I$			
4		$\downarrow()()$				
5		7				
6		7			$\tan(\beta_{1T})I \rightarrow 77$	
7		0				
8		$\downarrow()()$				
9		6	SETS PRINTG. IDENTIFIER TO ZERO			
160		$\uparrow()()$	START OF STAGE BY STAGE CALC.			
1		7				
2		7	$\tan(\beta_{1T})I_{J-1}$			
3		$\div$				
4		(				
5		$\uparrow()()$				
6		8				
7		1	$(\lambda)_{J-1}$			
8		X				
9		)	$(\lambda)_{J-1}^2$			
170		=	$\tan(\beta_{1T})I$			
1		$\downarrow()()$				
2		7				
3		7			$\tan(\beta_{1T})I \rightarrow 77$	
4		INV	$\cot(\beta_{1T})I$			
5		X				
6		$\uparrow()()$				
7		1				
8		0	Nu			
9		$\div$	$Nu \cot(\beta_{1T})I$			
180		(				
1		$\uparrow()()$				
2		0				
3		2	$\gamma - 1$			
4		a^x				
5		.				
6		5				
7		)	$\sqrt{\gamma - 1}$			
8		=	$(Nu_1)I = (Nu / \sqrt{\gamma - 1}) \cot(\beta_{1T})I$			
9		$\downarrow()()$				
190		7				
1		6			$(Nu_1)I \rightarrow 76$	
2		$\uparrow()()$				
3		7				
4		7	$\tan(\beta_{1T})I$			
5	E CODE	103	$(\beta_{1T})I^{\text{RAD}}$			
6		$R \rightarrow ^\circ$	$(\beta_{1T})I^\circ$			
7		$\downarrow()()$				
8		5				
9		0			$(\beta_{1T})I \rightarrow 50$	

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
20	0	SIN/COS	$\sin(\beta_{IT})_J$			
	1	+				
	2	(				
	3	1	1			
	4	-				
	5	HALT	$(D_{RT})_J$	$(D_{RT})_J$		
	6	$\downarrow () ()$				
	7	5				
	8	2				
	9	x			$(D_{RT})_J \rightarrow 52$	
21	0	HALT	$(\sigma_{RT})_J$	$(\sigma_{RT})_J$		
	1	$\downarrow () ()$				
	2	5				
	3	3				
	4	x			$(\sigma_{RT})_J \rightarrow 53$	
	5	2				
	6	)				
	7	$\div$				
	8	2NDFUNK	$\cos(\beta_{IT})_J$			
	9	$\div$				
22	0	HALT	λ_J	λ_J		
	1	$\downarrow () ()$				
	2	5				
	3	4				
	4	x	$(X_T)_J$		$\lambda_J \rightarrow 54$	
	5	+	$(X_T)_J^2$			
	6	$\downarrow ()$				
	7	1				
	8	1	1			
	9	=	$(X_T)_J^2 + 1$		$(X_T)_J^2 \rightarrow 1$	
23	0	$\downarrow ()$				
	1	2				
	2	$\uparrow () ()$			$1 + X_T^2 \rightarrow 2$	
	3	5				
	4	3	$(\sigma_{RT})_J$			
	5	x				
	6	2				
	7	$\div$	$2(\sigma_{RT})_J$			
	8	$\uparrow ()$				
	9	2	$X_T^2 + 1$			
24	0	x	$2\sigma_{RT} / (X_T^2 + 1)$			
	1	$\downarrow ()$				
	2	3				
	3	+	$(2\sigma_{RT} / (X_T^2 + 1))^2$		$2\sigma_{RT} / (X_T^2 + 1) \rightarrow 3$	
	4	(				
	5	$\uparrow ()$				
	6	1	X_T^2			
	7	-				
	8	(				
	9	2				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
2 5	0	X				
	1	$\uparrow () ()$				
	2	0				
	3	3	(σ_{RT})			
	4	X	$2(\sigma_{RT})$			
	5	)	$4(\sigma_{RT})^2$			
	6	$\div$	$X_T^2 - 4(\sigma_{RT})^2$			
	7	$\uparrow ()$				
	8	2	$X_T^2 + 1$			
	9	)	$(X_T^2 - 4(\sigma_{RT})^2) / (X_T^2 + 1)$			
2 6	0	=				
	1	$\sqrt{\quad}$				
	2	-				
	3	$\uparrow ()$				
	4	3	$2\sigma_{RT} / (X_T^2 + 1)$			
	5	=	$\sin(\beta_{2T})_J$			
	6	$\sin^{-1}/\cos^{-1}$	$(\beta_{2T})_J^R$			
	7	$R \rightarrow ^\circ$	$(\beta_{2T})_J^\circ$			
	8	$\downarrow () ()$				
	9	5				
2 7	0	9			$(\beta_{2T})_J \rightarrow 59$	
	1	ECODE	073	$\tan(\beta_{2T})_J$		
	2	$\downarrow () ()$				
	3	7				
	4	8			$\tan(\beta_{2T})_J \rightarrow 78$	
	5	$\div$				
	6	$\uparrow () ()$				
	7	7				
	8	7	$\tan(\beta_{1T})_J$			
	9	X				
2 8	0	$\uparrow () ()$				
	1	5				
	2	4	$(\lambda)_J$			
	3	CHSGN				
	4	+	$-\lambda \tan \beta_{2T} / \tan \beta_{1T}$			
	5	1				
	6	X	$1 - (\lambda \tan \beta_{2T} / \tan \beta_{1T})$			
	7	$\downarrow ()$				
	8	4			$1 - (\lambda \tan \beta_{2T} / \tan \beta_{1T}) \rightarrow 4$	
	9	HALT	Ω_J		Ω_J	
2 9	0	$\downarrow () ()$				
	1	5				
	2	5			$\Omega_J \rightarrow 55$	
	3	X				
	4	(				
	5	$\uparrow () ()$				
	6	1				
	7	0	Nu			
	8	X				
	9	)	Nu^2			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
300		+	$(\Delta T_w/T_0)_J$			
1		$\downarrow () ()$				
2		6				
3		5			$(\frac{\Delta T_w}{T_0})_J \rightarrow 65$	
4		$\uparrow () ()$				
5		6				
6		0	$(T_{t1}/T_0)_J$			
7		=	$(T_{t3}/T_0)_J$			
8		$\downarrow () ()$				
9		6				
310		6			$(\frac{T_{t3}}{T_0})_J \rightarrow 66$	
1		$\uparrow () ()$				
2		6				
3		5	$(\Delta T_w/T_0)_J$			
4		$\div$				
5		$\uparrow () ()$				
6		6				
7		0	$(T_{t1}/T_0)_J$			
8		x				
9		HALT	$(\eta_s)_J$	$(\eta_s)_J$		
320		$\downarrow () ()$				
1		5				
2		6			$(\eta_s)_J \rightarrow 56$	
3		+				
4		1				
5		a^*	T_{t3}^*/T_{t1}			
6		$\uparrow () ()$				
7		0				
8		3	$\gamma/(\gamma-1)$			
9		x	$(P_{t3}/P_t)_J$			
330		$\uparrow () ()$				
1		6				
2		1	$(P_{t1}/P_0)_J$			
3		=	$(P_{t3}/P_0)_J$			
4		$\downarrow () ()$				
5		6				
6		9			$(P_{t3}/P_0)_J \rightarrow 69$	
7		$\uparrow () ()$				
8		1				
9		0	Nu			
340		$\div$				
1		$\uparrow () ()$				
2		7				
3		7	$\tan(\beta_{1T})_J$			
4		x	$Nu/\tan(\beta_{1T})_J$			
5		$\div$	$[Nu/\tan(\beta_{1T})_J]^2$			
6		2				
7		$\div$	$[Nu \cot(\beta_{1T})_J]^2/2 = Z_J$			
8		$\downarrow () ()$				
9		7				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
350		5			$Z_T \rightarrow 75$	
1		$\uparrow() ()$				
2		6				
3		0	$(T_{t1}/T_0)_J$			
4		CHSGN				
5		+				
6		1				
7		a^x	$1 - Z_J / (T_{t1}/T_0)_J = T_1 / T_{t1}$			
8		$\uparrow() ()$				
9		0				
360		3	$\gamma / (\gamma - 1)$			
1		x	$(P_1/P_{t1})_J$			
2		$\uparrow() ()$				
3		6				
4		1	$(P_{t1}/P_0)_J$			
5		=	$(P_1/P_0)_J$			
6		$\downarrow() ()$				
7		6				
8		3			$(P_1/P_0)_J \rightarrow 63$	
9		$\uparrow() ()$				
370		6				
1		0	$(T_{t1}/T_0)_J$			
2		-				
3		$\uparrow() ()$				
4		7				
5		5	Z_J			
6		=	$(T_1/T_0)_J$			
7		$\downarrow() ()$				
8		6				
9		2			$(T_1/T_0)_J \rightarrow 62$	
380		$\uparrow() ()$				
1		5				
2		4	λ			
3		a^x				
4		4				
5		x	λ^4			
6		$\uparrow() ()$				
7		7				
8		5	Z_J			
9		CHSGN				
390		+	$-\lambda^4 Z_J$			
1		$\downarrow()$				
2		5			$-\lambda^4 Z_J \rightarrow 5$	
3		1	1			
4		a^x	$1 - \lambda^4 Z_J = (T_3/T_{t3})$			
5		$\uparrow() ()$				
6		0				
7		3	$\gamma / (\gamma - 1)$			
8		x	(P_3/P_{t3})			
9		$\uparrow() ()$				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
4 0	0	6				
	1	9	$(P_{t3}/P_0)_J$			
	2	=	$(P_3/P_0)_J$			
	3	↓()()				
	4	7				
	5	2				
	6	↑()()				
	7	6				
	8	6	$(T_{t3}/T_0)_J$			
	9	+				
4 1	0	↑()				
	1	5	$-\lambda^4(Nu^2/2) \cot^2(\beta_{13})$			
	2	÷	$(T_3/T_0)_J$			
	3	↓()()				
	4	7				
	5	1				
	6	↑()()				
	7	7				
	8	2	$(P_3/P_0)_J$			
	9	x	(P_0/P_3)			
4 2	0	↑()()				
	1	1				
	2	1	$\dot{m}_{REF}$			
	3	÷	$\dot{m}_{REF}(P_0/P_3)$			
	4	HALT				
	5	↓()()				
	6	5				
	7	8				
	8	÷	$(\dot{m}_{REF}/K_3)(P_0/P_3)$			
	9	(				
4 3	0	↑()()				
	1	5				
	2	4	λ_J			
	3	x				
	4	)	λ_J^2			
	5	÷				
	6	↑()()				
	7	1				
	8	0	Nu			
	9	x				
4 4	0	↑()()				
	1	7				
	2	7	$\tan(\beta_{1T})_J$			
	3	CHSGN				
	4	+				
	5	1				
	6	=				
	7	√	r_3			
	8	↓()()				
	9	7				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
450		3			(r_3) $\rightarrow$ 73	
1		$\uparrow ()$			J	
2		4	$1 - \left(\frac{\lambda \tan \beta_{2T}}{\tan \beta_{1T}} \right) J$			
3		X				
4		$\uparrow () ()$				
5		7				
6		7	$(\tan \beta_{1T}) J$			
7		$\div$				
8		2				
9		=	$(Y_T) J$			
460		$\downarrow () ()$				
1		7				
2		9			$(Y_T) J \rightarrow 79$	
3		$\uparrow () ()$				
4		5				
5		0	$(\beta_{1T}) J$			
6		-				
7		$\uparrow () ()$				
8		5				
9		9	$(\beta_{2T}) J$			
470		=	$\beta_{1T} - \beta_{2T} = \Delta \beta_T$			
1		$\downarrow () ()$				
2		6				
3		7			$\Delta \beta_T \rightarrow 67$	
4		0	$\uparrow$			
5		0				
6		0	FILLER			
7		0				
8		0	$\downarrow$			
9		0				
480		$\uparrow () ()$	$(\beta_{1T}) J$			
1		5				
2		0				
3		1	$\uparrow$			
4		.	PRINTING IDENTIFIER			
5		0	INCREMENT			
6		0				
7		0				
8		0	$\downarrow$			
9		$\downarrow ()$				
490		+				
1		6				
2		$\uparrow ()$				
3		6	CHANGE OF PRINTG. IDENTIFIER			
4	ECODE	177				
5		PRINTA			$(\beta_T) J$	
6		$\uparrow () ()$				
7		5				
8		2	$(DRT) J$			
9		PRINTA			$(DRT) J$	

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
5 0	0	$\uparrow()$				
	1	5				
	2	3	$(\sigma_{2T})_J$			
	3	PRINT A				$(\sigma_{2T})_J$
	4	$\uparrow()$				
	5	5				
	6	4	λ_J			
	7	PRINT A				λ_J
	8	$\uparrow()$				
	9	5				
5 1	0	9	$(\beta_{2T})_J$			
	1	PRINT A				$(\beta_{2T})_J$
	2	$\uparrow()$				
	3	6				
	4	7	$(\Delta\beta_T)_J$			
	5	PRINT A				$(\Delta\beta_T)_J$
	6	ECODE 065	PAPER ADVANCE			
	7	$\uparrow()$				
	8	5				
	9	5	Ω_J			Ω_J
5 2	0	PRINT A				
	1	$\uparrow()$				
	2	5				
	3	6	$(\eta_s)_J$			
	4	PRINT A				$(\eta_s)_J$
	5	ECODE 176	PRINT LINE OF DOTS			
	6	$\uparrow()$				
	7	6				
	8	0	$(T_{E1}/T_0)_J$			
	9	PRINT A				$(T_{E1}/T_0)_J$
5 3	0	$\uparrow()$				
	1	6				
	2	1	$(P_{E1}/P_0)_J$			
	3	PRINT A				$(P_{E1}/P_0)_J$
	4	ECODE 065	PAPER ADVANCE			
	5	$\uparrow()$				
	6	6				
	7	2	$(T_1/T_0)_J$			
	8	PRINT A				$(T_1/T_0)_J$
	9	$\uparrow()$				
5 4	0	6				
	1	3	$(p_1/p_0)_J$			
	2	PRINT A				$(p_1/p_0)_J$
	3	ECODE 176				
	4	ECODE 176	2 LINES OF DOTS			
	5	$\uparrow()$				
	6	6				
	7	6	$(T_{E3}/T_0)_J$			
	8	PRINT A				$(T_{E3}/T_0)_J$
	9	0	FILER			T_0/J

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
550		$\uparrow()()$				
1		6				
2		9	$(P_{t3}/P_0)_J$			
3		PRINTA				$(P_{t3}/P_0)_J$
4	ECODE	065	PAPER ADVANCE			
5		$\uparrow()()$				
6		7				
7		1	$(T_3/T_0)_J$			
8		PRINTA				$(T_3/T_0)_J$
9		$\uparrow()()$				
560		7				
1		2	$(P_3/P_0)_J$			
2		PRINTA				$(P_3/P_0)_J$
3	ECODE	176				
4	ECODE	176				
5	ECODE	176	3 LINES OF DOTS			
6		$\uparrow()()$				
7		5				
8		1	$(r_1)_J$			
9		PRINTA				$(r_1)_J$
570		$\uparrow()()$				
1		5				
2		7	$(k_1)_J$			$(k_1)_J$
3		PRINTA				
4	ECODE	065	PAPER ADVANCE			
5		$\uparrow()()$				
6		7				
7		3	$(r_2)_J$			
8		PRINTA				$(r_2)_J$
9		$\uparrow()()$				
580		5				
1		8	$(k_3)_J$			
2		PRINTA				$(k_3)_J$
3	ECODE	176	1 LINE OF DOTS			
4		HALT	READ REGISTERS 50-81 ON MAG. CARD			
5		BRANCH	ENTER 0 IF ALL STAGES HAVE BEEN PROCESSED			
6		=				
7		6				
8		4	GO TO BP 64 IF ALL STAGES HAVE BEEN PROCESSED			
9		$\uparrow()()$				
590		5				
1		0	$(\beta_{IT})_{J-1}$			
2		$\downarrow()()$				
3		8	SETTING-UP OF INLET			
4		0	CONDITIONS OF NEXT			
5		$\uparrow()()$	STAGE			$(\beta_{IT})_{J-1} \rightarrow 80$
6		5				
7		4	$(\lambda)_{J-1}$			
8		$\downarrow()()$				
9		8				

STEP	SOURCE	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
60	0		1			$\lambda_{J-1} \rightarrow 81$	
	1		$\uparrow () ()$				
	2		7				
	3		3	$(r_3)_{J-1}$			
	4		$\downarrow () ()$				
	5		5				
	6		1	$(r_1)_J$		$(r_1)_J \rightarrow 51$	
	7		$\uparrow () ()$				
	8		7				
	9		3	$(k_3)_{J-1}$			
61	0		$\downarrow () ()$				
	1		5				
	2		7	$(k_1)_J$		$(k_1)_J \rightarrow 57$	
	3		$\uparrow () ()$				
	4		6				
	5		6	$(T_{t3}/T_0)_{J-1}$			
	6		$\downarrow () ()$				
	7		6				
	8		0	$(T_{t1}/T_0)_J$		$(T_{t1}/T_0)_J \rightarrow 60$	
	9		$\uparrow () ()$				
62	0		6				
	1		9	$(P_{t3}/P_0)_{J-1}$			
	2		$\downarrow () ()$				
	3		6				
	4		1	$(P_{t1}/P_0)_J$		$(P_{t1}/P_0)_J \rightarrow 61$	
	5		$\uparrow () ()$				
	6		7				
	7		1	$(T_3/T_0)_{J-1}$			
	8		$\downarrow () ()$				
	9		6				
63	0		2	$(T_1/T_0)_J$		$(T_1/T_0)_J \rightarrow 62$	
	1		$\uparrow () ()$				
	2		7				
	3		2	$(p_3/p_0)_{J-1}$			
	4		$\downarrow () ()$				
	5		6				
	6		3	$(p_1/p_0)_J$		$(p_1/p_0)_J \rightarrow 63$	
	7		JUMP				
	8		1				
	9		6	TO BPT 16 FOR NEW STAGE			
64	0		$\uparrow () ()$				
	1		6				
	2		9	$(P_{t3}/P_0)_d$			
	3		a^x				
	4		$\uparrow () ()$				
	5		0				
	6		6	$(\gamma-1)/\gamma$			
	7		-				
	8		1				
	9		$\div$				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
650		(				
1		↑() ()				
2		6				
3		6	$(T_{t3}/T_0)d$			
4		-				
5		1				
6		)				
7		=	η_c			
8		↓() ()				
9		1				
660		2			$\eta_c \rightarrow 12$	
1		↑() ()				
2		0				
3		6	$(\gamma-1)/\gamma$			
4		x				
5		↑() ()				
6		0				
7		0	R_a			
8		x				
9		HALT	T_0	T_0		
670		↓() ()				
1		1				
2		3			$T_0 \rightarrow 13$	
3		=				
4		$\sqrt{\quad}$	$\sqrt{\frac{\gamma-1}{\gamma} R_a T_0}$			
5		INV				
6		x				
7		HALT	P_0	P_0		
8		↓() ()				
9		1				
680		4			$P_0 \rightarrow 14$	
1		x				
2		π				
3		÷				
4		4				
5		x				
6		(				
7		HALT	D_T	$D_T = 2R_T$		
8		↓() ()				
9		1				
690		5			$D_T \rightarrow 15$	
1		x				
2		)				
3		x				
4		↑() ()				
5		1				
6		1	m_{REF}			
7		x				
8		↓() ()				
9		1				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
700		6			m → 16	
1		3				
2		2				
3		.				
4		1				
5		7				
6		4	g			
7		=	$\dot{w}$ (lbm/s)			
8		↓() ()				
9		1				
710		7				
1		↑() ()				
2		6				
3		6	$(T_{t3}/T_0)d$			
4		-				
5		1				
6		x	$(T_{t3}/T_0)d - 1$			
7		↑() ()				
8		1				
9		3	T_0			
720		x				
1		↑() ()				
2		0				
3		4	C_p			
4		x				
5		↑() ()				
6		1				
7		6	m			
8		÷				
9		5				
730		5				
1		0				
2		=	HP			
3		↓() ()				
4		x				
5		8			HP → 18	
6	E CODE	176	1 LINE OF DOTS			
7		↑() ()				
8		1				
9		4	P_0 (psia)			
740		PRINTA				P_0
1		↑() ()				
2		1				
3		3	T_0 (°R)			
4		PRINTA				T_0
5		↑() ()				
6		1				
7		5	D_T (in.)			
8		PRINTA				D_T
9	E CODE	065	PAPER ADVANCE			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
75	0	$\uparrow()()$				
	1	6				
	2	9	$(P_{t3}/P_0)d$			
	3	PRINT A				(P_{t3})
	4	$\uparrow()()$				$(P_0)d$
	5	1				
	6	2	η_c			
	7	X				
	8	1				
	9	0				
76	0	0				
	1	=	$\eta_c(\%$			
	2	PRINT A				$\eta_c\%$
	3	E CODE 065	PAPER ADVANCE			
	4	0	↑ FILLER			
	5	0	↓			
	6	0				
	7	0				
	8	$\uparrow()()$				
	9	1				
77	0	7	$\dot{w}$ (lbm/s)			
	1	PRINT A				$\dot{w}$
	2	E CODE 065	PAPER ADVANCE			
	3	SET D.P	SET D.P. TO ZERO			
	4	0				
	5	$\uparrow()()$				
	6	1				
	7	8	HP			
	8	PRINT A				HP
	9	E CODE 176	1 LINE OF DOTS			
78	0	$\uparrow()()$				
	1	1				
	2	3				
	3	X				
	4	$\uparrow()()$				
	5	0				
	6	4	c_p			
	7	=				
	8	$\sqrt{\quad}$				
	9	X				
79	0	$\uparrow()()$				
	1	1				
	2	0	N_u			
	3	X	U_T (ft/s)			
	4	PRINT X				U_T
	5	7				
	6	2				
	7	0				
	8	$\div$				
	9	π				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
800		$\div$				
1		$\uparrow()()$				
2		1				
3		5	D_T			
4		=	$N(rpm)$			
5		PRINT A				N
6	E CODE	176	1 LINE OF DOTS			
7		SET D.P.	Set D.P to 3			
8		3				
9		1				
810		-				
1		$\uparrow()()$				
2		7	$(r_i)_I$			
3		$\div$				
4		2				
5		=				
6		$\uparrow()()$				
7		x				
8		1				
9		5	$D_T \rightarrow (l_i)_I (i_n)$			
820		PRINT A				$(l_i)_I$
1		1				
2		-				
3		$\uparrow()()$				
4		7				
5		3	$(r_3)_{I_{max}}$			
6		$\div$				
7		2				
8		=				
9		$\uparrow()()$				
830		x				
1		1				
2		5	$D_T \rightarrow (l_3)_{I_{max}} (i_n)$			
3		PRINT A				$(l_3)_{I_{max}}$
4	E CODE	176	1 LINE OF DOTS			
5		SET D.P.	Set D.P. to 4			
6		4				
7		HALT	END OF CALCULATIONS			
8						
9						
840						
1						
2						
3						
4						
5						
6						
7						
8						
9						

REGISTER	CONTENTS 1	CONTENTS 2	CONTENTS 3
0 0	R_G		
1	γ		
2	$\gamma-1$		
3	$\gamma/(\gamma-1)$		
4	C_p		
5	$1/(\gamma-1)$		
6	$(\gamma-1)/\gamma$		
7	-		
8	$\cot(\beta_{1T})x$		
9	-		
1 0	N_u		
1	$\dot{m}_{REF}$		
2	η_c		
3	T_0		
4	P_0		
5	$D_T = 2 R_T$		
6	$\dot{m}$		
7	$\dot{w}$		
8	HD		
9			
2 0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
3 0			
1			
2	SEE NEXT PAGE		
3			
4			
5			
6			
7			
8			
9			
4 0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

MAIN STORAGE BOOKKEEPING

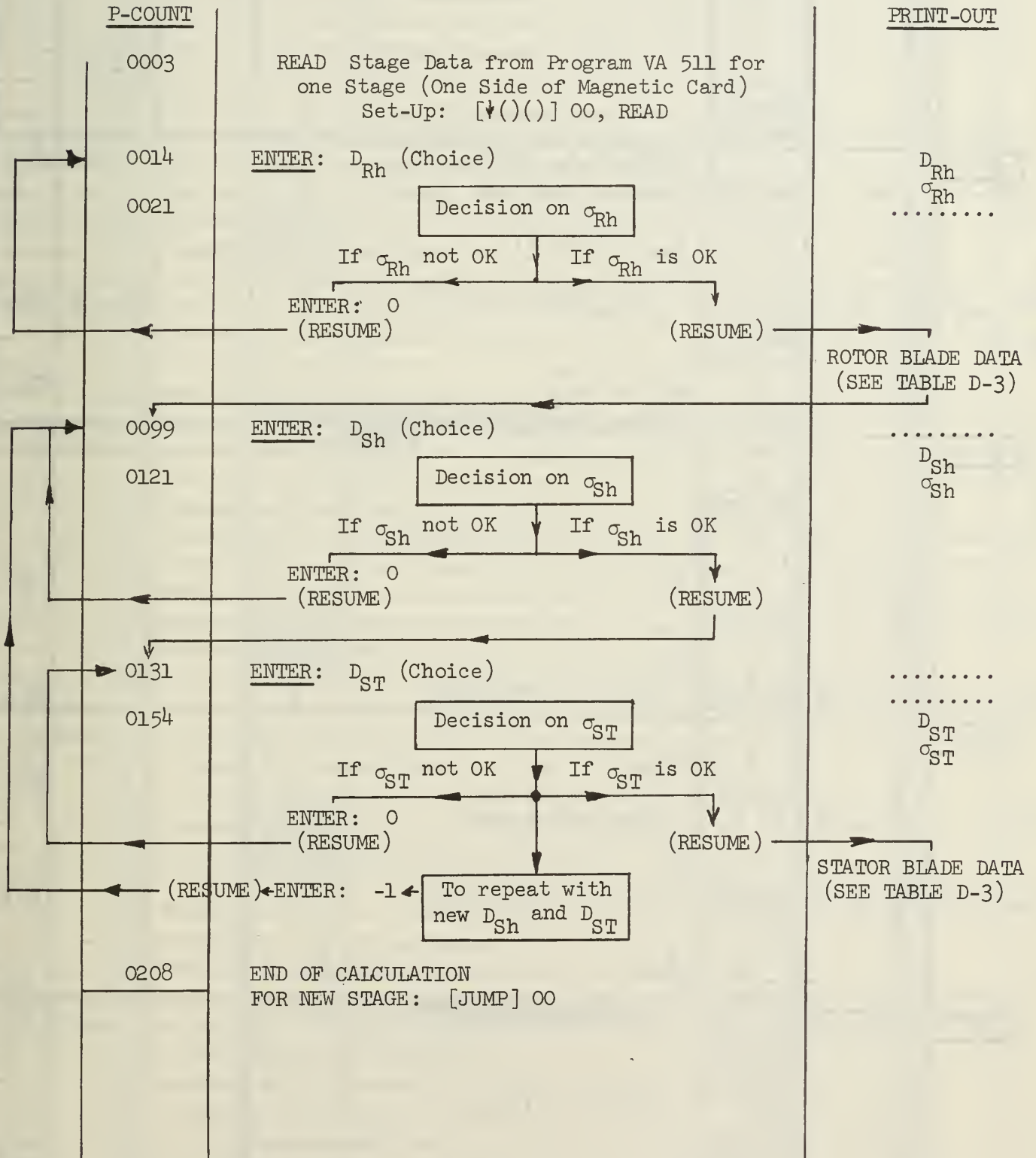
REGISTER	CONTENTS 1	CONTENTS 2	CONTENTS 3
5 0	β_{1T}	↑	
1	r_1		
2	D_{RT}		
3	σ_{RT}		
4	λ		
5	Ω		
6	η_s		
7	k_1		
8	k_3		
9	β_{2T}		
6 0	T_{t1}/T_0		
1	P_{t1}/P_0		
2	T_1/T_0	STAGE DATA, 32 REGISTERS WHICH MUST BE READ ON ONE SIDE OF A MAGNETIC CARD FOR USE IN PROGRAM 512. (SEE OP. INSTR. PROGRAM 511)	
3	P_1/P_0		
4	—		
5	$\Delta T_w/T_0$		
6	T_{t3}/T_0		
7	$\Delta \beta_T = \beta_{1T} - \beta_{2T}$		
8	—		
9	P_{t3}/P_0		
7 0	—		
1	T_3/T_0		
2	P_3/P_0		
3	r_3		
4	—		
5	$Z_J = Nu^2 \cot^2(\beta_{1T})_J / 2$		
6	$Nu_1 = Nu \cot(\beta_{1T})_J / \sqrt{x-1}$		
7	$\tan \beta_{1T}$		
8	$\tan \beta_{2T}$		
9	γ_T		
8 0	$(\beta_{1T})_{J-1}$	↓	
1	$(\lambda)_{J-1}$		
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

APPENDIX C: PROGRAM VA 512 FOR
MONROE 1880-22 PROGRAMMABLE CALCULATOR

BLADING DATA OF MULTI-STAGE AXIAL
COMPRESSOR WITH IMPULSE BLADINGS
(USED IN CONJUNCTION WITH PROGRAM VA 511)

OPERATING INSTRUCTIONS PROGRAM VA 512 (MONROE 1880-22 CALCULATOR)

BLADING DATA OF STAGES OF MULTI-STAGE AXIAL
COMPRESSOR WITH IMPULSE BLADING
(Set-Up: LOAD MAGNETIC CARDS OF PROGRAM AT BRANCH PT. 00)



STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		SET D.P.				
1		4				
2		HALT	READ DATA FROM MAG. CARD (REG. 0-31) PROG. VA 511			
3		$\uparrow()$				
4		0				
5		1	r_1			
6		$\downarrow()$				
7		0			$r_1 \rightarrow 0$	
8		BRANCH				
9		IND/SYMB				
0		+	TO S.R. β_1, β_2 FOR β_{1h}, β_{2h}			
1	a^x	IND/SYMB	$\uparrow$ SYMBOLIC ADDRESS $[a^x]$			
2		a^x	$\downarrow$			
3		HALT	D_{Rh} (CHOICE)	D_{Rh}		
4		$\downarrow()$				
5		5	$\leftarrow$ PRINT A		$D_{Rh} \rightarrow 5$	D_{Rh}
6		BRANCH				
7		IND/SYMB				
8		X	TO S.R. σ_{Rh}			σ_{Rh}
9		HALT	{ IF σ_{Rh} O.K. $\rightarrow$ [RESUME]; IF NOT: ENTER "0"			
0		JUMP	$\rightarrow$ [RESUME]			
1		=				
2		IND/SYMB				
3		a^x				
4		$\uparrow()$				
5		0	r_1			r_1
6		PRINT A				r_1
7		$\uparrow()$				
8		5	D_{Rh}			
9		PRINT A				D_{Rh}
0		$\uparrow()$				
1		6	σ_{Rh}			σ_{Rh}
2		PRINT A				σ_{Rh}
3	E CODE	065	PAPER ADVANCE			
4		$\uparrow()$				
5		7	β_{1h}			β_{1h}
6		PRINT A				β_{1h}
7		$\uparrow()$				
8		8	β_{2h}			β_{2h}
9		PRINT A				β_{2h}
0	E CODE	065	PAPER ADVANCE			
1		BRANCH				
2		IND/SYMB				
3		$\sqrt{\quad}$	S.R. $\alpha_2, T_2/T_0$			
4		BRANCH				
5		IND/SYMB				M_{Vih} M_{Whh} M_{Wzh}
6		X	S.R. M_{Vi}, M_{Wi}, M_{Wz}			
7	E CODE	176	1 LINE OF DOTS			
8		0				
9		0				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		2	2			
1		X				
2		↑() ()				
3		0				
4		1	r_1			
5		+	$2r_1$			
6		1				
7		÷	$1 + 2r_1$			
8		3				
9		=	$r_1' = \frac{1}{3}(1 + 2r_1)$			
0		↓()				
1		0				
2		PRINT A				r_1'
3		BRANCH				
4		IND/SYMB				
5		Φ	PRINT-OUT DATA AT r_1' ($D_R', \sigma_R', \beta_1', \beta_2', M_{V1}', M_{W1}', M_{W2}'$)			
6		2	2			
7		+				
8		↑() ()				
9		0				
0		1	r_1			
1		÷	$2 + r_1$			
2		3				
3		=	$r_1'' = \frac{1}{3}(2 + r_1)$			
4		↓()				
5		0				
6		PRINT A				r_1''
7		BRANCH				
8		IND/SYMB				
9		Φ	PRINT-OUT DATA AT r_1'' ($D_R'', \sigma_R'', \beta_1'', \beta_2'', M_{V1}'', M_{W1}'', M_{W2}''$)			
0		1				
1		↓()				
2		0				
3		PRINT A				$r_{T=1}$
4		BRANCH				
5		IND/SYMB				
6		Φ	PRINT-OUT OF TIP DATA ($D_{RT}, \sigma_{RT}, \beta_{1T}, \beta_{2T}, M_{V1T}, M_{W1T}, M_{W2T}$)			
7		0				
8		0				
9		0				
0	1	IND/SYMB	↑ SYMBOLIC ADDRESS 1			
1		1	↓			
2		↑() ()				
3		2				
4		3	r_3			
5		↓()				
6		0				$r_3 \rightarrow 0$
7		HALT	ENTER: D_{Sh} [CHOICE]			
8		↑()				
9		1				$D_{Sh} \rightarrow 1$

SYMB. ADD. 1

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		$\downarrow () ()$				
1		4				
2		0			$D_{sh} \rightarrow 40$	
3		BRANCH				
4		IND/SYMB				
5		$\sqrt{\quad}$	TO S.R. α_2			
6		BRANCH				
7		IND/SYMB				
8		$\rightarrow$	TO S.R. σ_5			
9	E CODE	176	1 LINE OF DOTS			
0		$\uparrow ()$				
1		1	D_{sh}			
2		PRINTA				D_{sh}
3		$\uparrow ()$				
4		2	σ_{sh}			
5		$\downarrow () ()$				
6		4				
7		1				
8		PRINTA				σ_{sh}
9		HALT	IF σ_{sh} OK $\rightarrow$ [RESUME]; IF NOT ENTER "0"			
0		BRANCH	$\downarrow$ [RESUME]			
1		=				
2		IND/SYMB				
3		1				
4	2	IND/SYMB	$\uparrow$ SYMBOLIC ADDRESS 2			
5		2	$\downarrow$			
6		1				
7		$\downarrow ()$				
8		0			$\Gamma_T = 1$	
9		HALT	ENTER: D_{ST} [CHOICE]			
0		$\downarrow ()$				
1		1			$D_{ST} \rightarrow 1$	
2		$\downarrow () ()$				
3		4				
4		2			$D_{ST} \rightarrow 42$	
5		BRANCH				
6		IND/SYMB				
7		$\sqrt{\quad}$	TO S.R. α_2			
8		BRANCH				
9		IND/SYMB				
0		$\rightarrow$	TO S.R. σ_5			
1	E CODE	176				
2		176	2 LINES OF DOTS			
3		$\uparrow ()$				
4		1	D_{ST}			
5		PRINTA				D_{ST}
6		$\uparrow ()$				
7		2	σ_{ST}			
8		$\downarrow () ()$				
9		4				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		3			$\sigma_{ST} \rightarrow 43$	
1		PRINT A				σ_{ST}
2		HALT	IF σ_{ST} OK $\rightarrow$ [RESUME]; IF σ_{ST} NOT OK			
3		JUMP	ENTER "0" $\rightarrow$ [RESUME]; IF σ_{ST}			
4		=	AND σ_{sh} HAVE TO BE CHANGED			
5		IND/SYMB	ENTER "-1" $\rightarrow$ [RESUME]			
6		2				
7		JUMP				
8		-				
9		IND/SYMB				
0		1				
1	E CODE	065	PAPER ADVANCE			
2	E CODE	065	PAPER ADVANCE			
3		$\uparrow()$				
4		2				
5		3	r_3			
6		$\downarrow()$				
7		0			$r_3 \rightarrow 0$	
8		BRANCH				
9		IND/SYMB				
0		=	TO S.R. STATOR BLADE DATA FOR $r = r_3$			PRINT-OUT
1		2				
2		x				
3		$\uparrow()$				
4		2				
5		3	r_3			
6		+				
7		1				
8		$\div$				
9		3				
0		=	r_3'			
1		$\downarrow()$				
2		0				
3		BRANCH				
4		IND/SYMB				
5		=	TO S.R. STATOR BLADE DATA FOR $r = r_3'$			PRINT-OUT
6		2				
7		+				
8		$\uparrow()$				
9		2				
0		3	r_3			
1		$\div$				
2		3				
3		=	r_3''			
4		$\downarrow()$				
5		0				
6		BRANCH				
7		IND/SYMB				
8		=	TO S.R. STATOR BLADE DATA FOR $r = r_3''$			PRINT-OUT
9		0	FILLER			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
0		I				
1		↓()				
2		0			$r_2 \rightarrow 0$	
3		BRANCH				
4		IND/SYMB				
5		=	TO S.R. STATOR BLADE DATA FOR $r = r_T = 1$		PRINT-OUT	✓
6		HALT				
7		0				
8		0				
9		0				
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
210	+	IND/SYMB	↑ SYMBOLIC ADDRESS +			
1		+	↓			
2		↑()				
3		0	r			
4		x				
5		↑()()				
6		2				
7		7	$\tan \beta_{1T}$			
8		=	$\tan \beta_1$			
9		↓()				
0		1			$\tan \beta_1 \rightarrow 1$	
1	ECODE	103	β_1^R			
2		R → °	β_1°			
3		↓()				
4		7			$\beta_1 \rightarrow 7$	
5		SIN/COS				
6		2ND FCT	$\cos \beta_1$			
7		↓()				
8		3			$\cos \beta_1 \rightarrow 3$	
9		↑()				
0		0	r			
1		-				
2		(				
3		1				
4		÷				
5		↑()	SUBROUTINE			
6		0	r			
7		)	$\frac{1}{r}$	β_1, β_2 EQS. 6 & 7		
8		÷	$r - \frac{1}{r}$	SYMB ADDRESS +		
9		↑()()				
0		0				
1		4	λ			
2		x	$\lambda(r - \frac{1}{r})$			
3		↑()()				
4		2				
5		7	$\tan \beta_{1T}$			
6		+	$\lambda(r - \frac{1}{r}) \tan \beta_{1T}$			
7		(				
8		↑()()				
9		2				
0		8	$\tan \beta_{2T}$			
1		÷				
2		↑()				
3		0	r			
4		)	$\frac{1}{r} \tan \beta_{2T}$			
5		=	$\tan \beta_2$			
6		↓()				
7		2			$\tan \beta_2 \rightarrow 2$	
8	ECODE	103	β_2^R			
9		R → °	β_2°			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
260		↓ ()				
1		8	SUBROUTINE β_1, β_2		$\beta_2 \rightarrow 8$	
2		SIN/COS	SYMB. ADD. +			
3		2ND FUN	$\cos \beta_2$			
4		↓ ()				
5		4			$\cos \beta_2 \rightarrow 4$	
6		RESUME				
7	X	IND/SYMB	SYMBOLIC ADDRESS X			
8		X				
9		↑ () ()				
0		0				
1		4	λ			
2		÷				
3		↑ ()				
4		4	$\cos \beta_{2h}$			
5		-	$\lambda / \cos \beta_{2h}$			
6		(				
7		1				
8		-				
9		↑ ()				
0		5	D_{rh}			
1		÷	$1 - D_{rh}$			
2		↑ ()				
3		3	$\cos \beta_{1h}$			
4		)				
5		X	SUBROUTINE			
6		2	σ_{rh} (EQ. 44)			
7		=	SYMB. ADDRESS X			
8		INV				
9		X				
0		(				
1		↑ ()				
2		1	$\tan \beta_{1h}$			
3		-				
4		(				
5		↑ () ()				
6		0				
7		4	λ			
8		X				
9		↑ ()				
300		2	$\tan \beta_{2h}$			
1		)				
2		)				
3		=	σ_{rh} $\swarrow$ $\downarrow$ () ()		$\sigma_{rh} \rightarrow 35$	
4		↓ ()	3			
5		6	5		$\sigma_{rh} \rightarrow 6$	
6		PRINTA	ECODE 176 ILINE DOTS			σ_{rh}
7		RESUME				
8		0				
9		0				

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
310	÷	IND/SYMB	↑ SYMBOLIC ADDRESS ÷			
1	÷					
2	1		1			
3	-					
4	f()					
5	0	r				
6	÷	1-r				
7	(					
8	1	1				
9	-					
0		f() ()				
1	0		SUBROUTINE σ_R & D_R			
2	1	r_1	EQS. 48 & 11			
3	)	1-r ₁	& PRINT ROUTINE			
4	x		$D_R, \sigma_R, \beta_1, \beta_2$			
5	(					
6	f() ()		SYMB. ADDRESS ÷			
7	0					
8	3	σ_{RT}				
9	-					
0	(					
1	f() ()					
2	0					
3	1	r_1				
4	x					
5	f() ()					
6	3					
7	5	σ_{Rh}				
8	)	r_1, σ_{Rh}				
9	)	$\sigma_{RT} - \sigma_{Rh} r_1$				
0	-	$(\sigma_{RT} - r_1, \sigma_{Rh}) (\frac{1-r}{1-r_1})$				
1	f() ()					
2	0					
3	3	σ_{RT}				
4	÷					
5	f()					
6	0	r				
7	CHSGN	-r				
8	=	σ_R				
9	↓()					
0	6				$\sigma_R \rightarrow 6$	
1	INV	$1/\sigma_R$				
2	x					
3	f()					
4	3	$\cos \beta_1$				
5	x					
6	f() ()					
7	2					
8	9	γ_T				
9	÷					

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
36	0	f()				
1		0	r			
2		+				
3		1				
4		-	$1 + \frac{1}{r} \frac{\cos \beta_1}{\sigma_R} Y_r$			
5		(	SUBROUTINE			
6		f()	σ_R, D_R EQS. 48, 11			
7		0	PRINT $D_R, \sigma_R, \beta_1, \beta_2$			
8		4	SYMB. ADD $\frac{1}{r}$			
9		x				
0		f()				
1		3	$\cos \beta_1$			
2		÷				
3		f()				
4		4	$\cos \beta_2$			
5		)				
6		=	D_R			
7		PRINT A				D_R
8		f()				
9		6	σ_R			
0		PRINT A				σ_R
1	E CODE	065	PAPER ADVANCE			
2		f()				
3		7	β_1			
4		PRINT A				β_1
5		f()				
6		8	β_2			
7		PRINT A				β_2
8	E CODE	065	PAPER ADVANCE			
9		RESUME				
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						
0						
1						
2						
3						
4						
5						
6						
7						
8						
9						

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
3 9 0	V	IND/SYMB	↑ SYMBOLIC ADDRESS V			
1		V	↓			
2		2	2			
3		x				
4		f(X)				
5		2				
6		9	Y_T			
7		÷				
8		f() ()				
9		0				
0		4	λ			
1		÷				
2		f()				
3		0	r			
4		=	$\tan \alpha_2$			
5	E CODE	103	$\tan^{-1} = \alpha_2 R$			
6		$R \rightarrow ^\circ$	α_2			
7		f() ()				
8		3				
9		6			$\alpha_2 \rightarrow 36$	
0		SIN/cos	$\sin \alpha_2$			
1		f() ()				
2		3				
3		7				
4		2ND FUN	$\cos \alpha_2$			
5		f() ()				
6		3			$\cos \alpha_2 \rightarrow 38$	
7		8				
8		÷				
9		f() ()				
0		0				
1		4	λ			
2		x	$\cos \alpha_2 / \lambda$			
3		=	$(\cos \alpha_2 / \lambda)^2$			
4		INV	$\lambda^2 / \cos^2 \alpha_2$			
5		x				
6		f() ()				
7		2				
8		5	$Z = \frac{N u^2}{2} \cot^2 \beta_{1T}$			
9		CHSGN				
0		+	$-\frac{\lambda^2}{\cos^2 \alpha_2} Z$			
1		f() ()				
2		1				
3		6	T_{23}/T_0			
4		=	T_2/T_0			
5		f() ()				
6		3				
7		9			$T_2/T_0 \rightarrow 39$	
8		RESUME				
9						

STEP	SOURCE	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
44	0	X	IND/SYMB	{ SYMBOLIC ADDRESS X			
	1		X				
	2		↑() ()				
	3		1				
	4		2	T_1/T_0			
	5		√				
	6		INV	$1/\sqrt{T_1/T_0}$			
	7		X				
	8		↑() ()				
	9		2				
	0		6	$N_{u1} = (N_u / \sqrt{Pr}) \cot \beta_1 T$			
	1		÷	M_{V1}			
	2		PRINT X				M_{V1}
	3		↑()				
	4		3	$\cos \beta_1$			
	5		=	M_{W1}			
	6		PRINT A				M_{W1}
	7		↑() ()				
	8		3				
	9		9	T_2/T_0			
	0		√				
	1		INV	$1/\sqrt{T_2/T_0}$			
	2		X	SUBROUTINE			
	3		↑() ()	M_{V1}, M_{W1}, M_{W2}			
	4		0	EQS. 37, 36, 38, 39			
	5		4	λ			
	6		X	SYMBOLIC ADDRESS X			
	7		↑() ()				
	8		2				
	9		6	N_{u1}			
47	0		÷				
	1		↑()				
	2		4	$\cos \beta_2$			
	3		=	M_{W2}			
	4		PRINT A				M_{W2}
	5		RESUME				
	6		0				
	7		0				
	8		0				
	9		0				
	0						
	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
480	Φ	IND/SYMB	$\uparrow$ SYMBOLIC ADDRESS Φ $\uparrow$			
1	Φ		$\downarrow$			
2	BRANCH					
3	IND/SYMB					
4	+		TO S.R. β_1, β_2			
5	BRANCH					
6	IND/SYMB		SUBROUTINE ROTOR BLADE DATA			
7	$\div$		TO S.R. σ_R, D_R AT r			D_R
8	BRANCH		SYMBOLIC ADDRESS Φ			σ_R
9	IND/SYMB					β_1
						β_2
0	$\sqrt{\quad}$		TO S.R. $\alpha_2 \neq T_2/T_0$			
1	BRANCH					
2	IND/SYMB					M_{V1}
3	$\times$		TO SR M_{V1}, M_{W1}, M_{W2}			M_{W1}
4	ECODE	176	1 LINE OF DOTS			M_{W2}
5	RESUME					
6	0					
7	0					
8	0					
9	0					
500	$\uparrow$	IND/SYMB	$\uparrow$ SYMBOLIC ADDRESS $\uparrow$			
1	$\uparrow$		$\downarrow$			
2	$\uparrow() ()$		$\uparrow$			
3	3		$\left\{ \begin{array}{l} x \\ \uparrow() () \end{array} \right.$			
4	8		$\cos \alpha_2$ $\left\{ \begin{array}{l} 0 \end{array} \right.$			
5	-		$\lambda \cos \alpha_2$ $\left\{ \begin{array}{l} 4 [\lambda] \end{array} \right.$			
6	(					
7	1		1			
8	-					
9	$\uparrow()$		SUBROUTINE σ_s EQ. 51 SYMB ADD $\uparrow$			
0	1		D_s			
1	)		$1 - D_s$			
2	x		$\lambda \cos \alpha_2 - [1 - D_s]$			
3	2					
4	=		$2 [\lambda \cos \alpha_2 - (1 - D_s)]$			
5	INV					
6	x					
7	$\uparrow() ()$					
8	3					
9	7		$\sin \alpha_2$			
520	=		σ_s			
1	$\downarrow()$					
2	2					$\sigma_s \rightarrow 2$
3	RESUME					
4	0					
5	0					
6	0					
7	0					
8	0					
9	0					

STEP	SOURCE	SOURCE	COMMAND	COMMENTS	ENTER	STORE	PRINT
53	0	=	IND/SYMB	↑ SYMBOLIC			
	1		=	↓			
	2		1	1			
	3		-				
	4		↑()				
	5		0	r			
	6		÷	1-r			
	7		(				
	8		1	1			
	9		-				
	0		↑() ()				
	1		2				
	2		3	r ₃			
	3		)	1-r ₃			
	4		x	$\frac{1-r}{1-r_3}$			
	5		(				
	6		↑() ()				
	7		4				
	8		3	σ _{ST}			
	9		-				
	0		(				
	1		↑(X)				
	2		2				
	3		3	r ₃			
	4		x				
	5		↑() ()				
	6		4				
	7		1	σ _{sh}			
	8		)	r ₃ σ _{sh}			
	9		)	σ _{ST} - r ₃ σ _{sh}			
	0		-	$(\sigma_{ST} - r_3 \sigma_{sh}) \frac{1-r}{1-r_3}$			
	1		↑() ()				
	2		4				
	3		3	σ _{ST}			
	4		÷				
	5		↑()				
	6		0	r			
	7		CHSGN	-r			
	8		=	σ _S			
	9		↓()				
57	0		2			σ _S → 2	
	1		BRANCH				
	2		IND/SYMB				
	3		√	TO S.R. α ₂ & T ₂ /T ₀			
	4		↑()				
	5		0	r			
	6		PRINTA				r
	7		↑() ()				
	8		3				
	9		7	sin α ₂ √			

STEP	SOURCE	SOURCE	COMMAND	COMMENTS	ENTER	STORE	PRINT
58	0		$\div$				
	1		2				
	2		$\div$				
	3		$\uparrow()$				
	4		2	σ_3			
	5		+				
	6		1				
	7		-	$1 + \sin \alpha_2 \frac{1}{2\sigma_3}$			
	8		(				
	9		$\uparrow()()$				
	0		0				
	1		4	λ			
	2		x	SUBROUTINE STATOR			
	3		$\uparrow()()$	BLADE DATA (CONT. 1)			
	4		3	SYMBOLIC ADDRESS =			
	5		8	$\cos \alpha_2$			
	6		)	$\lambda \cos \alpha_2$			
	7		=	D_5			
	8		PRINT A				D_5
	9		$\uparrow()$				
	0		2	σ_3			
	1		PRINT A				σ_3
	2	E CODE	065	PAPER ADVANCE			
	3		$\uparrow()()$				
	4		3				
	5		6	α_2			
	6		PRINT A				α_2
	7	E CODE	065	PAPER ADVANCE			
	8		$\uparrow()()$				
	9		3				
	0		9	T_2/T_0			
	1		$\sqrt{\quad}$				
	2		INV	$1/\sqrt{T_2/T_0}$			
	3		x				
	4		$\uparrow()()$				
	5		2				
	6		6	Nu_1			
	7		$\div$				
	8		$\uparrow()()$				
	9		3				
62	0		8	$\cos \alpha_2$			
	1		x				
	2		$\uparrow()()$				
	3		0				
	4		4	λ			
	5		=	Mv_2			
	6		PRINT A				Mv_2
	7		$\uparrow()()$				
	8		2				
	9		1	T_3/T_0			

STEP	SYMBOL	COMMAND	COMMENTS	ENTER	STORE	PRINT
63	0	$\sqrt{\quad}$	$\sqrt{T_3/T_0}$			
	1	INV	$1/\sqrt{T_3/T_0}$ (CONT. 2)			
	2	x	SUBROUTINE STATOR			
	3	$\uparrow(\quad)(\quad)$	BLADE DATA			
	4	2	S.A. =			
	5	6	Nu_1			
	6	x				
	7	(				
	8	$\uparrow(\quad)(\quad)$				
	9	0				
64	0	4	λ			
	1	x				
	2	)	λ^2			
	3	=	M_{V3}			
	4	PRINT A				M_{V3}
	5	ECODE 065	PAPER ADVANCE			
	6	ECODE 176	1 LINE OF DOTS			
	7	RESUME				
	8					
	9					
	0					
	1					
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	0					
	1					
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	0					
	1					
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					

SCRATCH PAD MEMORY STORAGE

[illegible]

MAIN STORAGE BOOKKEEPING

REGISTER			CONTENTS 1	CONTENTS 2	CONTENTS 3
0	0	0	β_{1T}	↑	
	1		r_1		
	2		D_{RT}		
	3		σ_{RT}		
	4		λ		
	5		Ω_h		
	6		γ_s		
	7		k_1		
	8		k_2		
	9		β_{2T}		
1	0	0	T_{E1}/T_0		
	1		P_{E1}/P_0		
	2		T_1/T_0	READ FROM MAGNETIC CARD OF DATA OF PROGRAM 511 (32 SIDES OF MAG. CARD) FOR EACH STAGE	
	3		p_1/p_0		
	4		—		
	5		$\Delta T_w/T_0$		
	6		$\Delta T_3/T_0$		
	7		$\Delta \beta_T = \beta_{1T} - \beta_{2T}$		
	8				
	9		P_{E3}/P_0		
2	0	0			
	1		T_3/T_0	↓	
	2		p_3/p_0		
	3		r_3		
	4				
	5		$\bar{z} = Nu^2 \cot^2 \beta_{1T} / 2$		
	6		$Nu_1 = Nu \cot \beta_{1T} / \sqrt{\gamma - 1}$		
	7		$\tan \beta_{1T}$		
	8		$\tan \beta_{2T}$		
	9		γ_T		
3	0	0	$(\beta_{1T})_{J-1}$	↓	
	1		$(\lambda)_{J-1}$		
	2				
	3				
	4				
	5		σ_{Rh}		
	6		α_2		
	7		$\sin \alpha_2$		
	8		$\cos \alpha_2$		
	9		T_2/T_0		
4	0	0	D_{Sh}		
	1		σ_{Sh}		
	2		D_{ST}		
	3		σ_{ST}		
	4				
	5				
	6				
	7				
	8				
	9				

APPENDIX D: FORMS FOR PRINT-OUTS
OF PROGRAMS VA 511 AND VA 512

PROGRAM VA511

TABLE D-1 :PRINT-OUT OF RESULTS OF STAGE DATA CALCULATIONS

CONFIGURATION # : _____

STAGE#		STAGE#	
β_{1T}		β_{1T}	
D_{RT}		D_{RT}	
σ_{RT}		σ_{RT}	
λ		λ	
β_{2T}		β_{2T}	
$\Delta\beta_T$		$\Delta\beta_T$	
Ω		Ω	
η_S		η_S	
.....			
T_{t1}/T_0		T_{t1}/T_0	
P_{t1}/P_0		P_{t1}/P_0	
T_1/T_0		T_1/T_0	
P_1/P_0		P_1/P_0	
.....			
T_{t3}/T_0		T_{t3}/T_0	
P_{t3}/P_0		P_{t3}/P_0	
T_3/T_0		T_3/T_0	
P_3/P_0		P_3/P_0	
.....			
r_1		r_1	
k_1		k_1	
r_3		r_3	
k_3		k_3	
.....			

PROGRAM VA511

TABLE D-2 : PRINT-OUT OF RESULTS OF OVERALL COMPRESSOR PERFORMANCE

CONFIGURATION # : _____

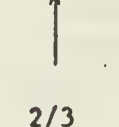
Molecular Weight of Gas	M
Specific Heat Ratio of Gas	γ
.....	
First Stage Data:Relative Tip Flow Angle	β_{1T}
Hub/Tip Ratio	r_1
Blockage Factor	k_1
.....	
Referred Tip Speed	N_u
Referred Mass Flow Rate	$\dot{m}_{REF}$
.....	
.....	
Total Inlet Pressure (psia)	P_0
Total Inlet Temperature (°R)	T_0
Tip Diameter of Stages (inches)	
.....	
Overall Total Pressure Ratio	
Overall Total-to-Total Efficiency (%)	
.....	
Weight Flow Rate (lbm/s)	
.....	
Blading Drive Power (HP)	
.....	
Peripheral Speed at Rotor Tip (ft/s)	
Rotative Speed (rpm)	
.....	
Blade Height of First-Stage Rotor(in.)	
Blade Height of Last Stator (in,)	
.....	

TABLE D-3 : PRINT-OUT OF BLADING DATA

CONFIGURATION #: _____

STAGE #: _____

ROTORSTATOR

	r_h D_{Rh} σ_{Rh}		r_h D_{Sh} σ_{Sh}
HUB	β_{1h} β_{2h}	HUB	α_{2h}
	M_{V1} M_{W1h} M_{W2h}		M_{V2} M_{V3}
	r D_R σ_R		r D_S σ_S
1/3 BLADE HEIGHT	β_1 β_2	1/3 BLADE HEIGHT	α_2
	M_{V1} M_{W1} M_{W2}		M_{V2} M_{V3}
	r D_R σ_R		r D_S σ_S
2/3 BLADE HEIGHT	β_1 β_2	2/3 BLADE HEIGHT	α_2
	M_{V1} M_{W1} M_{W2}		M_{V2} M_{V3}
	r_T D_{RT} σ_{RT}		r_T D_{ST} σ_{ST}
TIP	β_{1T} β_{2T}	TIP	α_{2T}
	M_{V1} M_{W1} M_{W2}		M_{V2} M_{V3}

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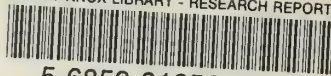
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